DEPLOYMENT METHODOLOGY FOR FIRE DEPARTMENTS

THE DEPARTMENT OF
HOUSING AND URBAN
DEVELOPMENT

Office of
Policy Development
And Research

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PREFACE

This report is intended for the planning staffs of fire departments and related municipal agencies. Its purpose is to inform them about recently developed procedures to assist them in locating firehouses and in analyzing other deployment decisions.

Preparation of this report was sponsored by the Office of Policy Development and Research, U.S. Department of Housing and Urban Development (HUD). Other Rand reports sponsored by this HUD office include documentation of models for deployment of emergency services, users' manuals for such models, case studies of applications in selected cities, and lecture notes for a training course in deployment of emergency services. The lecture notes cover the same topics as this report and provide examples of visual aids and demonstrations of computer programs that can be used in presenting this material to a class:

> Jan M. Chaiken, Edward J. Ignall, and Warren E. Walker, *A Training Course in Deployment of Emergency Services*, R-1784/1-HUD (*Instructor's Manual*); R-1784/2 (*Student's Manual*),* The Rand Corporation, September 1975.

HUD plans future publications for fire chiefs and municipal executives, describing how fire deployment analysis can improve their departments' operations.

Also available is a report that has approximately the same content as the present report but is written for police planners:

> Jan M. Chaiken, *Patrol Allocation Methodology for Police Departments*, R-1852-HUD, The Rand Corporation, September 1975.

Further information on any of this material can be obtained by writing to the address given in the Appendix.

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*The student's manual is identical with the instructor's manual except that it omits references to readings and visual aids. It can only be ordered in multiple copies for members of a class whose instructor is using the instructor's manual.

SUMMARY

This report reviews mathematical methods that have been developed to assist fire departments in analyzing and improving the deployment of their fire-fighting resources. Most of these methods are incorporated in computer programs that have been carefully tested and applied in a number of large and small cities across the country. The methods and computer programs are described and compared, but they are not discussed in detail. Instead, the reader is directed to the appropriate source documents.

The key issues of fire deployment analysis are:

- Determining the number of fire companies to have on duty city-wide and in each region of the city; this may vary by time of day or by season of the year.
- Determining the specific location for each fire company.
- Developing a policy for redeploying fire companies when large numbers of companies are busy at fires.
- Developing a policy for dispatching fire companies to alarms.

The present number and arrangement of fire companies in most cities are based more on historical factors (for example, where volunteer companies were first organized) than on a careful analysis of actual needs. Several computer-based models are described that can be used to assist managers in making a more rational determination of the number of fire companies to have and where they should be located.

A method for redeploying fire companies is described. It is based on minimizing average travel times to fires, using up-to-the-minute information about the status of all fires in progress and all fire companies.

The development of improved dispatching policies concentrates on determining the correct number of fire companies to send to each alarm--that is, to send more companies to potentially more serious alarms and fewer companies to alarms that are not likely to be very serious.

Computer-based methods depend on collecting data adequate for estimating the likelihood that an incoming alarm signals a serious fire.

The report concludes with a discussion of the steps that should be followed in performing a deployment study. These include identifying the policy questions to be analyzed and the methods to be used, collecting and processing appropriate data, finding people with the relevant analytical skills, assembling a representative project team, acquiring and running the computer programs, and developing policy recommendations based on the analysis.

ACKNOWLEDGMENTS

The methodology described in this report has been developed over the course of almost eight years by a large team of analysts at The New York City-Rand Institute. It would be impossible to give each the credit he or she deserves, although the list of references provides some idea of the diverse nature of the contributions to this effort.

Particular thanks must go to the New York City Fire Department and its Commissioner, John T. O'Hagan, for providing continuous and unswerving support during this period, for serving as a laboratory for testing the methodology, and for creating a complementary team in the Bureau of Planning and Operations Research who worked with us in developing, testing, analyzing, and implementing the various pieces of the methodology.

We also wish to thank Alan Siegel and Hartley Fitts of the Office of Policy Development and Research, U.S. Department of Housing and Urban Development, for having faith in the methods and for sponsoring their documentation and their testing in cities throughout the country.

We thank Robert Baumgardner, Peter Kolesar, and Arthur Swersey for helpful comments on an earlier draft of this report.

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Chapter 1

INTRODUCTION

Deciding how many fire companies to have and how to locate and dispatch them is becoming increasingly important in this time of rising fire incidence and shrinking city budgets. This report reviews mathematical methods that have been developed to assist fire departments in answering these deployment questions. The mathematical models have been used to analyze existing deployment policies and to develop improved policies in several cities across the country, ranging from New York City and Denver to Wilmington and Tacoma.

We will describe the various models that are available, the principles on which the models operate, what they can be used for, when and how to use them, and the data needed for each one. We hope such information will help departments discover whether they need any of the models and, if so, which ones would be most appropriate in their circumstances.

The reader should be aware, however, that issues that should and do occupy the attention of fire department administrators, such as community support and relations between labor and management, may far outweigh considerations of efficiency that arise from viewing the firefighting function in a narrow technical or mathematical sense. Thus, policy analysts and planning officers must address operational questions in a context of both explicit and implicit administrative, legal, and political constraints. They cannot expect mathematical methods and models, such as those described here, to tell them the "best" solution to whatever problem their department faces, and they must be prepared to use all such methods with caution, imagination, and common sense.

When used with care, mathematical models provide several benefits to the planner. First, they can help identify deficiencies in current deployment policies by letting the planner calculate performance statistics that were not previously available to the department. Second, they permit the planner to consider and analyze a large number of alternative deployment policies, whereas only one or two alternatives can be considered seriously if tedious manual calculations are required. Third, some of the models may suggest alternatives that are preferable to the ones that were initially considered.

WHAT IS "DEPLOYMENT ANALYSIS"?

The general subject of deployment analysis includes a variety of topics, some of which can be addressed using mathematical models and others not. We have limited the discussion in this report to several deployment issues that can be analyzed using mathematical models. These concern the manner in which fire companies are located and dispatched. They can be divided into two groups, *strategic* issues and *tactical* issues.

Strategic Issues

Strategic refers to long-range planning issues. In this report, we will concentrate on the following strategic deployment questions:

1. *How many fire companies should be on duty?* This may be a planning decision related to the department's budget for the next several years, or it may concern the appropriate variation in company levels by time of day or by season of the year.
2. *How many fire companies should be allocated to each region of the city?*[*] This question refers to the location of fire companies in a general sense and not to specific locations of firehouses; for example, how many companies should be in the central business district and how many in residential parts of the city?
3. *Where should the city's fire companies be located?* This question refers to choosing sites for fire stations. Many factors must be considered that do not arise when general allocation questions are being analyzed. These include the availability

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[*] The term "city" refers to the geographical region of interest. This, of course, may be a county or any fire protection district. Several fire departments may cooperate in deployment analysis, in which case the "city" is several communities.

of land, direction of one-way streets, traffic conditions, and so forth.

Tactical Issues

By *tactical*, we do not mean tactics on the fireground, but rather we refer to issues that arise from moment to moment during the course of a day. The most important tactical issues addressed here are:

1. *Dispatching policy.* This encompasses all the rules and procedures used by dispatchers, including:
    a. *How many fire companies of each type should be sent to an incoming alarm?* The answer may vary among departments according to the number of firemen in each fire company. It may also depend on the availability of companies at the time of the alarm and what is known about the nature of the incident at the time the dispatch is made. For example, more companies might be sent to a telephone report of flames in a building than to a signal from a street alarm box.
    b. *Which particular fire companies should be dispatched?* Most fire departments dispatch the units that are closest to the location of an incident. However, in cities where alarm rates are high and workloads are heavy, there may be conditions under which it is better not to send the closest units.
2. *Redeployment policy.* Higher-alarm fires need many companies quickly, and most departments dispatch all of the closest available units. This leaves a large region unprotected, so companies from farther away are often moved to some of the empty firehouses for the duration of the incident. If a department uses such a policy, which is variously called *redeployment*, *relocation*, or *move-up*, rules must be developed as to when and how it is to be accomplished.

Issues Not Discussed in this Report

The same models that are used to analyze the above deployment issues can, in some instances, be used to study equipment-oriented questions, such as whether a department should implement a computer-assisted dispatching system. But such topics fall outside the domain of "deployment analysis" and therefore will be omitted. Also omitted are a variety of deployment issues of considerable concern to fire departments but for which suitable modeling approaches have not yet been developed. These include the selection of the appropriate types and mix of apparatus and the determination of the number of firemen to man each unit. We also recognize that there are areas besides deployment in which a fire department can make changes that will improve its effectiveness or reduce its costs (improved fire prevention strategies, use of new fire-fighting and communications equipment, etc.). But a discussion of methods for evaluating the effects of such changes is beyond the scope of this report.

MEASURES OF PERFORMANCE

Although there is agreement on the primary objectives of the fire department--to minimize the loss of life and property caused by fire--fire deployment analysts are not able to base their studies directly on these objectives, because there are no reliable methods for estimating the effect of changes in deployment policies on the objectives. For example, if the number of fire companies on duty is doubled, or halved, no one can state with any degree of certainty what will happen to fire deaths or to the amount of property that is destroyed by fire. This is an important topic for research but is so difficult to resolve that no results of direct use for deployment analysis can be expected for many years.

To analyze deployment policies, then, we must use *proxy* measures of performance. These are substitutes for true performance measures, and they fall generally into two groups. The first consists of departmental characteristics that are related to the insurance rates charged the city's property owners. These rates are based on the city's insurance grade, which is established periodically by the Insurance Services

Office (ISO) after a survey of the city--including its water supply, fire department, and building department. The insurance grade depends in part on the number of companies on duty and other deployment decisions [10].*

Therefore, certain types of deployment changes could potentially result in an increase or decrease in the total amount paid for insurance by the city's property owners, which might be an important consideration in deciding whether or not the proposed changes should be made. However, as reported by the National League of Cities (Ref. 9, p. 43), calculating the effect of a change in insurance grade on total premiums paid is both difficult and subject to error. In addition, because a city's insurance grade will stay fixed through a large range of deployment changes, it is of little assistance in choosing among certain alternative policies.

The second group of proxy measures are numerical quantities that can be calculated easily and reliably, and that are related to the performance of a fire department. Use of these measures relies on the fact that some kinds of changes can be identified as desirable even if we do not know exactly how much better they are. Travel time is one such proxy measure. If a change in deployment policy that uses the existing fire-fighting resources can reduce travel times to all incidents that are of concern to the department, this is a desirable change. Or, if the existing level of travel times can be achieved at lower cost, such a change is also desirable. Although such "ideal" changes cannot often be achieved in practice, they do illustrate that the desirability of a specific change can often be identified without knowing its precise effect on the fire department's performance.

From such considerations, we arrive at the following five measures that are both practical to calculate and relevant for deployment analysis. (A longer list of measures of fire department performance, and the uses to which each can be put, is given in Ref. 27.) We will indicate in succeeding chapters which measure(s) are appropriate for each deployment issue.

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*Numbers in square brackets indicate references to be found at the end of this report. The references provide additional information about topics discussed in the text.

Response Time

Response time is the length of time from the moment the fire department is notified until a fire company is on the scene and ready to operate. It is of interest because faster response times will presumably lead to fewer fire fatalities and less property damage. As indicated in Fig. 1, response time includes a *dispatching time*, which is the time from the receipt of the alarm until the unit is alerted to respond by the dispatcher; a *turnout time*, which is the time required for the unit to leave its quarters and start moving after it has been dispatched; a *travel time*, which is the length of time between the start of the unit's trip and its arrival at the scene; and a *setup time*, which is the time required for the unit to prepare and position its equipment at the scene before beginning fire fighting. In most situations, the only component of response time that is affected by changes in the deployment of fire companies is the travel time. Therefore, deployment analysis focuses on changes in travel times.

Response Time by Type of Unit. Actually, there are several travel-time measures that are useful. First, because different types of units (for example, engines and ladders) perform different functions at a fire, it is important to distinguish travel times for each type of equipment.

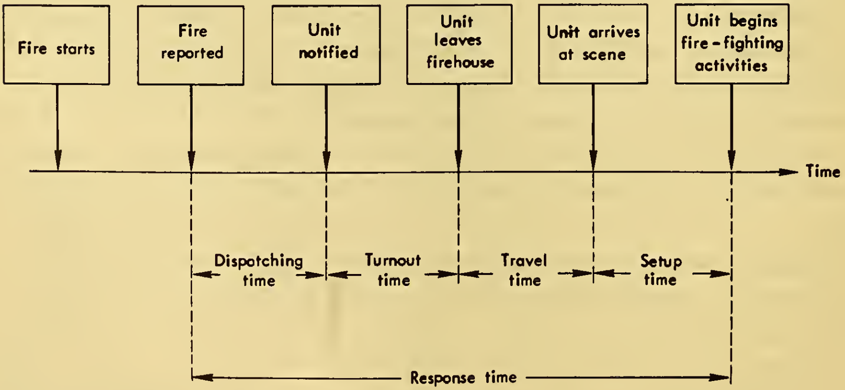

Fig. 1—The components of response time

Second, because two units of the same type working together may be able to take an action that neither could handle alone, the travel time of each arriving piece of equipment is important. Therefore, in evaluating alternative strategic deployment policies we must consider the list of travel times for engines, ladders, and other fire-fighting units that are assigned to respond to each potential incident location (for example, a street alarm box) in the city.

Summary Information about Travel Times. Although in principle the planner is interested in every travel time, a computer program that simply listed all the travel times would overwhelm him with too much information. For policy analysis he needs appropriate summarized statistics. For example, if he is considering moving one firehouse (without changing anything else), he knows that travel times near the old firehouse site will increase and those near the new site will decrease. A computer program can tell him *where* and *by how much* travel times will change.

Average travel times are useful summary statistics. These could be calculated separately for all locations where the travel times increased and for all locations where they decreased. The planner might also want to know the number of incident locations where the travel time is more than, say, three minutes, and how that number is affected by the policy change. Some types of policy changes can affect travel times all over the city. In such cases, the planner will want to look at averages and other summary statistics for various groups of incident locations--by region of the city, by company response area, by degree of hazard, etc.

Weighted Averages. The average travel time to actual alarms can be found by weighting the travel time to each location by the alarm rate at that location. However, because travel times to structural fires are far more critical than travel times to incidents that turn out to be false alarms, it might be more desirable to weight the travel time to each location by the structural fire rate at that location. This will provide an estimate of the average travel time to a structural fire occurring within that group of locations.

Unweighted Averages. Although the average travel time to actual alarms is an important measure of performance, a fire department must also make sure that fire companies are located close to all hazardous locations, not only to those with long histories of fires. Fires rarely occur in well-run nursing homes, chemical plants, hospitals, and high-rise buildings. But when one does, the resulting loss of life and property can be substantial. Therefore, another average travel time that is important is the average to all locations in a region of the city (giving equal weight to each potential fire location). This unweighted average travel-time measure is sometimes referred to as the *coverage* provided to a region.

Availability

It is of little comfort to know that there is a firehouse one block away if the fire company stationed there is rarely in the house. Calculation of the travel-time measures described above usually assume that when an alarm from a specific location is received, the companies designated to respond will be available. When this assumption is inappropriate we must consider each company's *unavailability*, which is the fraction of time it is busy. This tells us how often it will happen that alarms in the company's first-due area will suffer a travel-time delay because the responding companies are located in more distant firehouses than would usually be the case. (Unavailability is also a measure of the company's workload; see below.)

More refined unavailability measures indicate not only how often the first-due company to a particular location will be unavailable, but also how often both the first- and second-due companies will be unavailable, etc.*

Initial Response Adequacy

A measure that is useful in comparing dispatching policies is the proportion of alarms for which the initial response was appropriate.

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*This kind of information is usually not calculated by simple models such as the ones that will be discussed in Chapter 4.

Sending *fewer* units than are needed may prevent or slow fire fighting and rescue operations until the required companies are dispatched and arrive, and thus add to life and property loss. Sending *more* units than are needed means needless responses for the extra companies and the loss of the ability to dispatch them to other incidents, at least until the nature of the alarm becomes known. While calculations of travel times, if performed with sufficient accuracy, will reflect the adequacy of initial response, it is often easier to consider response adequacy separately.

Fire Company Workloads

In New York City, some fire companies respond to more than 6000 alarms per year. As a result, one of the important considerations in evaluating any new deployment policy in New York is its effect on company workloads. Workload is not as serious a problem in most cities, although, as fire departments begin to take over emergency medical service functions, they are finding that their fire companies are much busier than in the past. Even when the absolute sizes of company workloads are not high enough to cause problems, the departments may be concerned about maintaining a reasonable balance of work among their companies. For these reasons, another yardstick for evaluating alternative policies is a workload measure--for example, the average number of times per day that a fire company would respond to alarms, or the average amount of time it would spend working at fires.

Cost

The measures of performance discussed above can, of course, always be improved by spending more money. Therefore, in evaluating various possible deployment policies, we must either compare equal-cost alternatives or identify clearly the difference in cost among alternatives.

The direct cost of having an existing company respond to another alarm is very small--gasoline plus wear and tear on the apparatus--if the alternative is to have it remain in the firehouse. In contrast, the cost of creating a new company is very large, and it is important to note that the capital cost of the apparatus and the firehouse is small when compared with the cost of manning the company. For example, consider the cost for a city to field one extra fire company, manned by three firemen and an officer, around the clock. The extra company would require approximately 15 firemen and 5 officers (assuming a 40-hour work week) at a salary and benefit cost that usually amounts to over $300,000 per year. The yearly capital cost (debt service) on a $500,000 firehouse, assuming it can be used for at least forty years, would then account for less than 10 percent of the total cost of maintaining the company. The comparison is even more dramatic if two or three different types of companies share a single firehouse.

Consequently, the cost of a deployment policy is often adequately represented by the number of men it requires on the payroll, rather than by the number of firehouses needed or the number of responses that will be made.

OVERVIEW

Now that we have presented the deployment issues and the measures of performance used to compare different deployment policies, we will discuss the methodologies that analysts have developed to assist fire departments in resolving these issues. In the next chapter, we begin with a nontechnical description of the mathematical principles that underlie all the models. We then present procedures for gathering and analyzing the data required to use the models. Next, we discuss the various individual methodologies in turn: Chapter 4 gives methods for helping decide how many companies to have and where to locate them. The next two chapters treat tactical questions: Chapters 5 and 6 give methods for redeployment and initial dispatch, respectively. (For reference, the Table of Contents gives the page numbers where the individual models and methods are discussed.) The final chapter discusses the steps that should be followed in performing a deployment study. Further information on any of the models and methods can be obtained by writing to the address given in the Appendix.

Chapter 2

GENERAL DEPLOYMENT PRINCIPLES

In this chapter we describe the basic principles that underlie the analysis of all deployment issues. Some of these principles are well-known facts about the operations of a fire department that are mentioned here only because it is important to keep them in mind. Others are simple mathematical formulas that have been found useful for calculating performance measures. The equations are simple enough to be stated in words, with only a few mathematical symbols. The planner who understands the principles in this chapter will be able to answer some deployment questions with quick calculations. For more complicated questions, the general principles will help him make educated guesses about how to proceed with the analysis, but they cannot substitute for the detailed calculations performed by computer-based models.

First, let us define a few expressions that will be used in what follows. The term *alarm* means any incident to which fire companies are dispatched. The *alarm rate* is the average number of alarms per hour; and a fire company that is unavailable for dispatch because it has responded to an alarm is said to be *busy*. The *service time* of a fire company at an alarm (also called its *work time*) is the length of time it is unavailable for dispatch because it is involved with the incident. This includes the company's travel time, its on-scene service time, and its recovery time (if any). If more than one unit of a given type is dispatched to an alarm, the number of *company-hours* spent at the incident is the sum of the service times (in hours) of all the companies of that type. In the next chapter we will discuss how alarm rates and service times can be estimated or predicted in advance.

Most fire departments deploy two basic types of fire-fighting companies: engine (or pumper) companies and ladder (or truck) companies, which perform very different functions at a fire. The deployment of each type of company is ordinarily analyzed separately.* Thus, when we refer to one or the other we are simply illustrating a principle that applies to either one of them.

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*However, depending on the question at hand, it is sometimes necessary to treat both types at the same time.

NUMBER OF COMPANIES BUSY

At any given moment, a dispatcher can easily determine whether none of the engine companies in the city is busy, one engine is busy, two are busy, or whatever. If he periodically wrote down the number of engines busy (say, every minute) and then averaged these numbers at the end of an hour, a tour, a day, or some other period of time, he would have the *average number of engine companies busy* during that period.

The first general principle is an equation relating the average number of busy engine companies to the alarm rate and the amount of work done at each alarm:

$$\begin{pmatrix}\text{Average number}\\ \text{of engine}\\ \text{companies busy}\end{pmatrix} = (\text{alarm rate}) \times \begin{pmatrix}\text{average engine}\\ \text{company-hours}\\ \text{per alarm}\end{pmatrix} . \tag{1}$$

Although this equation may appear to be a meaningless manipulation of two numbers to calculate a third number, it is valuable because it is possible to *predict*, from past experience, the approximate alarm rate and average number of company-hours per alarm. Once these predictions have been made, the equation tells us how many companies will be busy on the average.

For example, suppose it has been predicted that an average of four alarms will be received per hour and that the average engine company-hours per alarm is 0.5. Then we predict that, on the average, 4 × 0.5 = 2 engine companies would be busy.[*]

The equation need not be applied to a city as a whole. It applies to any region of the city in any specified time period. It requires only that the average alarm rate and average engine (or ladder) company-hours per alarm correspond to the region and time period.

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[*] If the average number of *ladder* company-hours per alarm is used on the right-hand side of the equation, the left side will be the average number of ladder companies busy at alarms. Adding the average number of engines and ladders busy gives the average number of fire compani busy.

What use can be made of information concerning the average number of companies busy in different regions at different times? This information tells us, first, that *the number of companies of each type located in a region at a given time should at least equal the average number expected to be busy*; otherwise, units from outside the region will be responding into the region very often. (Below we will see that sensible performance standards require a substantially larger number of units than the average number expected to be busy.)

Note also that the average number of companies available in a region is equal to the total number of companies located in the region minus the average number busy. That is:

$$\left(\begin{array}{c}\text{Average number}\\ \text{of companies}\\ \text{available}\end{array}\right) = \left(\begin{array}{c}\text{total number}\\ \text{of companies}\end{array}\right) - \left(\begin{array}{c}\text{average number}\\ \text{of companies}\\ \text{busy}\end{array}\right). \qquad (2)$$

UNPREDICTABILITY OF ALARMS

Alarms do not occur at orderly, predictable times. Moreover, the number of companies and the length of time required to handle an alarm are not exactly the same for all alarms. Were it not for these unpredictable aspects of alarms, it might be possible to allocate a smaller number of fire companies than are in fact needed.

For example, suppose (contrary to fact) that in a small area of the city one alarm occurred regularly on the hour and half-hour, and each incident required one engine company and one ladder company to work exactly 30 minutes (including travel times to and from the incident and recovery time, if any). Then, one engine and one ladder could handle all the alarms. If there were two engines and two ladders on duty, one of each type would always be available to respond.

But alarms do not occur on the hour and the half-hour. Indeed, if an *average* of two alarms per hour is expected during a certain period of time (say, Friday from 4 p.m. to midnight), some of the hours may have no alarms at all, while others may have five or more. Studies have shown that the number of alarms that occur in a large number of such hours will be distributed as if they came from a probability distribution known as the *Poisson distribution.*[*] In the case of an average alarm rate of two alarms per hour, the Poisson distribution tells us that, if we observe how many alarms occur in many hours,

14% of the hours will have no alarms,
27% of the hours will have 1 alarm,
27% of the hours will have 2 alarms,
18% of the hours will have 3 alarms,
9% of the hours will have 4 alarms,
4% of the hours will have 5 alarms,
1% of the hours will have 6 or more alarms.

Adding together all the percentages for three alarms or more, we now see that a single engine and ladder would not be adequate to handle all the alarms in 32 percent of the hours. In fact, if typical variations in service times are taken into account, even with two engines and two ladders on duty there will be no unit available one-third of the time.

Thus we see that, although the absolute minimum number of companies needed to handle alarms in this example is one engine and one ladder, the unpredictability of when alarms occur results in a need for more than twice this minimum, if acceptable levels of availability are to be achieved.

AVERAGE TRAVEL TIME

As discussed in Chapter 1, the travel times in a region constitute an important measure of fire protection that is used in deployment analysis. It is the only component of response time that is affected by changes in the deployment of fire companies. There are many ways to estimate travel times. For example, the travel distances between firehouses and incident locations in a region could be clocked on an odometer or measured on a map; these distances could be translated into travel times by timing actual trips or assuming a constant travel speed. Other possibilities are discussed in Chapter 4. Here we present a relatively simple procedure that has been tested in many cities and has been found to produce very good estimates of *average* travel times.[*] The procedure involves two steps. First, we estimate average travel *distance*; then we convert travel distance into travel *time*.

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[*] For a description of the Poisson distribution and its widespread applicability to random events such as accidents and radioactive decay of particles, see any textbook on queuing theory or probability theory, for example, Ref. 23.

The Square-Root Law

The simple relationship that has been found to give good estimates of average travel distance is called the *square-root law*. To describe this law, we again consider engine companies and suppose that no more than one engine company is located in a single firehouse. If a region has area A (in square miles) and there are N engine companies available at the moment of dispatch, the square-root law states that the average travel distance (in miles) for the first-arriving engine is given by the equation

$$\begin{pmatrix}\text{Average}\\ \text{travel}\\ \text{distance}\end{pmatrix} = (\text{constant}) \times \sqrt{\frac{A}{N}}\ . \tag{3}$$

From studies in several cities, the constant for the first-arriving engine company has been found to be approximately equal to 0.6.[†] For the average distance traveled by the second-arriving engine company, a similar relationship holds, but the constant is larger, being approximately 1.0. The constant itself is of little interest. The importance of the relationship is its *form*: Distance increases in proportion to the *square root of the area*, and it decreases in inverse proportion to the *square root of the number of engines*. This relationship was derived through mathematical modeling [20], and its validity was confirmed by analysis of data from a fire operations simulation model (which we will describe later) [16]. (Of course, the square-root law also holds for ladder companies, if N is taken to be the number of ladder companies available in the region.)

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[*] In Chapter 4 we also discuss the importance of estimating travel times to particular locations identified by the department as special hazards. The general principles described here apply primarily to average travel times in regions, rather than to particular travel times

[†] This varies from 0.5 to 0.7 in urban areas. It depends on the street configuration and how the companies are distributed geographically. The correct value can be determined in any particular city by collecting data showing the travel distance for each response and the number of companies available at the time of the response. For rough calculations, the value 0.6 is adequate.

When some firehouses have two or more engine companies, the square-root law needs to be adjusted. For the first-arriving engines, the number N on the right-hand side of equation (3) should be interpreted to mean the "number of houses that have at least one engine company available." This adjustment reflects the fact that for a fixed total number of engine companies, consolidated firehouses will always lead to average travel distances for the first-arriving engine that are higher than when every firehouse has a single engine. In fact, the square-root law permits us to calculate the effect of consolidation. For example, if 9 engine companies were available, one to a firehouse, in a 16-square-mile region, the square-root law would estimate average travel distance to be

$$.6 \times \sqrt{16/9} = .80 \text{ miles.}$$

If, as a result of consolidating firehouses, these 9 engines were located in 6 different houses, average travel distance to alarms would increase to

$$.6 \times \sqrt{16/6} = .98 \text{ miles.}$$

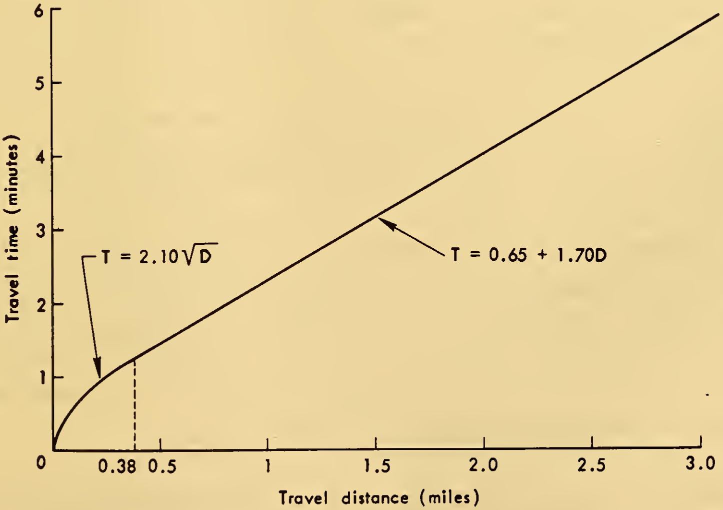
We return to the case of one engine company per firehouse. Because the number of available fire companies will vary over time, the square-root law cannot be used directly to estimate the average travel distance to alarms over the course of an hour or several hours. However, it has been found [20] that if the *average* number of available engine companies in a region is not too small (say, over 2.0), a reasonable approximation i

$$\begin{pmatrix}\text{Average}\\ \text{travel}\\ \text{distance}\end{pmatrix} = (\text{constant}) \times \sqrt{\frac{A}{\begin{matrix}\text{average number of engine}\\ \text{companies available}\end{matrix}}}\ . \tag{4}$$

(Recall that the average number of engine companies available can be calculated from equation (2).) The constant here is generally slightly smaller than the constant in equation (3), but for rough-cut estimates one can continue to use the same numbers: 0.6 for first-arriving engine and 1.0 for second-arriving engine. For more careful estimates, see Ref. 20.

Converting Travel Distance to Travel Time

Having established this relationship, we need only convert travel distance into travel *time*. Studies of the travel characteristics of fire companies [12,22] have shown that travel time is related to travel distance according to a curve such as the one shown in Fig. 2.



Source: Average of empirical results from Denver, Trenton, Wilmington, and Yonkers

Fig. 2—The relationship between travel time and travel distance

A curve of this shape would result if a company had to accelerate to a constant cruising speed, maintain it for a period, and then decelerate to its destination. For small distances, it would never reach cruising speed, which yields the curved part of the relationship in Fig. 2.

The mathematical function that has been found to represent this relationship best has the following form:

$$T = \begin{cases} c\sqrt{D} & \text{when D is less than or equal to d,} \\ a + bD & \text{when D is greater than or equal to d,} \end{cases} \tag{5}$$

where D is the travel distance in miles and T is the travel time in minutes.* The constants of the function (a, b, c, and d) can be estimated for a specific city by collecting data on the responses of fire companies over a period of time (see Chapter 3). However, as a result of collecting such data in several cities, we have found, surprisingly, that the values of these parameters vary little from city to city or by time of day. Therefore, a city may be able to obtain useful travel-time estimates without carrying out such a data collection effort by using the equation shown in Fig. 2:

$$T = \begin{cases} 2.10\sqrt{D} & \text{when D is less than or equal to 0.38 mile,} \\ 0.65 + 1.70 \times D & \text{when D is greater than or equal to 0.38 mile.} \end{cases}$$

To estimate the average travel time in a region, we first use the square-root law (equation (4)) to estimate the average travel distance in the region. This distance is then used as the value of D on the right-hand side of the travel-time equation. (Although this use of the square-root law and the travel-time equation involves several approximations, it has been found to be reasonable [19].)

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*When D is equal to d, either form of the equation must give the same result. In other words, the constants a, b, c, and d must be properly related to each other.

RELATIONSHIP BETWEEN NUMBER OF COMPANIES AND PERFORMANCE LEVELS

The number of companies needed to meet desired performance levels does not increase proportionately with the alarm rate or the performance level. For example, it is very important to realize that (1) when the alarm rate doubles, it is *not* necessary to double the number of fire companies to achieve the same travel-time levels (it requires fewer than twice the number); and (2) to cut travel-time levels in half requires many more than twice the number of fire companies.

These two conclusions follow from the dependence of travel distances and travel time on the alarm rate and the number of companies that is embodied in the square-root law and the travel-time equation. These relationships reveal that a large percentage change in the number of companies assigned to a region yields a small change in average travel distance and an even smaller change in average travel time.

> Example. Consider a region with the characteristics given in Table 1. We shall show that by keeping the same average travel time when the alarm rate doubles requires an 18-percent increase in the number of companies. This is considerably smaller than the 100-percent increase in alarms. However, improving average travel time by a certain percentage requires the number of companies to be increased by more than that percentage. In the same example, a 64-percent increase in the number of companies assigned brings only a 25-percent reduction in average travel distance and a 17-percent reduction in average travel time. (To halve the average travel time would require, in this case, about a 900-percent increase in the number of companies!) See Fig. 3.

Table 1

CHARACTERISTICS OF ILLUSTRATIVE REGION

Area (square miles)	16
Original number of engine companies assigned	11
Alarm rate (incidents per hour)	4
Engine company-hours per alarm	0.5

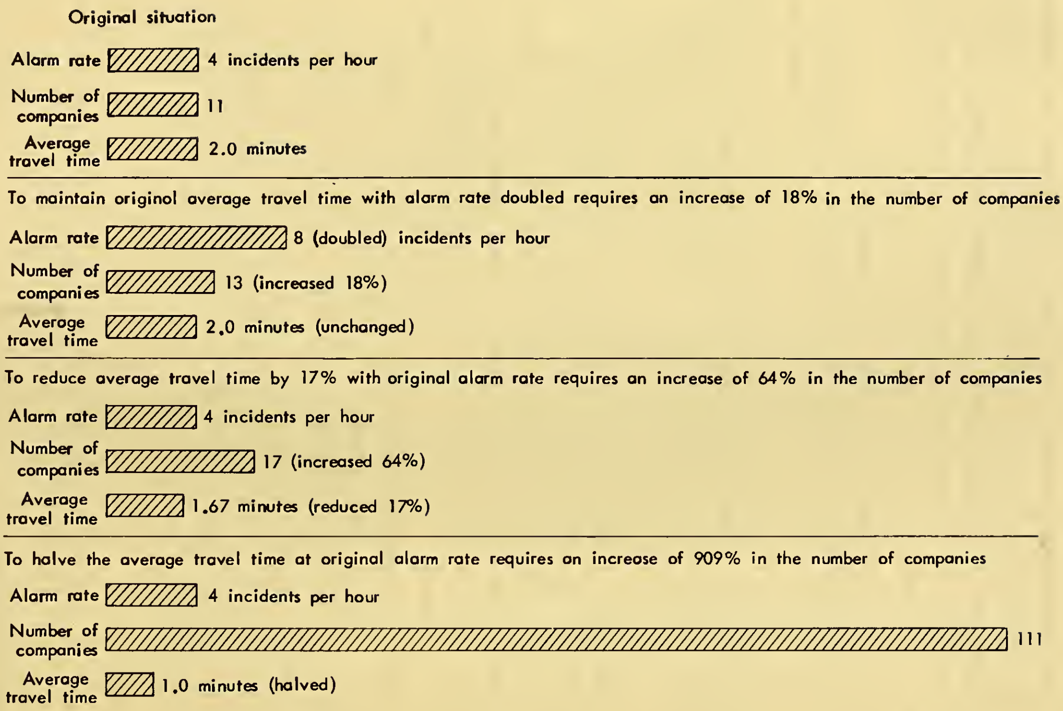

Fig. 3—Relating alarm rate and number of companies to travel time

In the situation specified in Table 1, an average of 2 (= 4 × .5) engines are busy in the region. Consequently, an average of 9 (= 11 - 2) engines are available. Using the square-root law, with the constant = .6, the average distance traveled by the first-arriving engine is .8 miles (= $.6 \sqrt{16/9}$). Using the travel-time equation shown in Fig. 2, the average travel time of the first-arriving engine is 2.01 minutes (= .65 + 1.70 × .8).

Suppose that the alarm rate doubled to 8 per hour, and that the average engine-hours per alarm stayed at .5. An average of 4 (= 8 × .5) engines would be busy, 2 more than before the alarms went up. If we add 2 engines to the original 11 (an 18-percent increase), we see that an average of 9 engines will be available. Consequently, the square-root law will still predict .8 mile for average response distance, and the travel-time equation will still give 2.01 minutes for average travel time.

Let us consider different circumstances. Suppose the alarm rate is the original 4 per hour and we are interested in improving travel times. For this purpose 7 more engines might be assigned to the region--an increase of 64 percent (= 100 × 7/11) in the number assigned. Then, an average of 16 (= 11 + 7 - 2) engine companies would be available. Using the square-root law, the average distance traveled by the first-arriving engine would be .6 mile (= $.6 \sqrt{16/16}$). Using the travel-time equation, the average travel time of the first-arriving engine would be 1.67 minutes (= .65 + 1.7 × .6). That is, travel distance would drop by 25 percent (= 100 × (.8 - .6)/.8) and travel time would drop by 17 percent (= 100 × (2.01 - 1.67)/2.01).

Finally, consider the calculation of the number of engines needed to give an average travel time of 1.0 minutes (half of 2.01). Looking at Fig. 2, travel time of 1.0 minutes is on the curved portion of the relationship ($T = 2.10 \sqrt{D}$). Inserting T = 1.0 and solving for D, we find that an average travel distance of .23 mile (= $(1.0/2.10)^2$) is implied. Inserting this distance in the square-root law gives

$$.23 = .6 \times \sqrt{16/\text{average number of engine companies available}}$$

Solving this equation for the average number of engines available gives 109 (= $16(.6/.23)^2$). Because on the average 2 engines are busy, we would need to assign 111.

Chapter 3

COLLECTION AND ANALYSIS OF DATA

To use the methods and models described in this report, planners must have access to estimates of alarm rates and other information. This chapter describes ways of getting the required numbers. First, we discuss what is needed to use the square-root law and other general principles, and then turn to what is needed to study allocation and other specific deployment issues.

To make use of the general principles described in Chapter 2, knowledge of, or reasonable estimates of, at least the following data are essential:

- The rates at which serious fires and other types of alarms occur in different geographical regions of the city* at different times of day.
- The average company working hours in different regions at different times of day.
- The constants in the square-root law (equation (4)).
- The constants in the relationship between travel time and travel distance (equation (5)).

We have specified that data are needed for "different regions at different times of day" because citywide year-round averages for the performance measures can conceal inequities and problems. For example, despite a reasonable citywide value for, say, average travel time, there can be unacceptably long travel times in some parts of the city. And a reasonable average daily workload may arise from a very heavy workload during the busy times of day, and little work at other times.

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*For certain types of deployment analyses, the planner will want to collect data for a region larger than the city being studied. This might be the case if mutual aid agreements provide for responding into neighboring jurisdictions.

In addition to the above estimates, to address the specific deployment issues discussed in Chapters 4, 5, and 6, the following information is needed:

Deployment Issue	Information Required
Allocation	Potential severity of fires and other indicators of hazards not reflected in actual alarms in different regions of the city.
Firehouse siting	Alarm rates in small areas--for example, at individual alarm boxes or groups of boxes or areas several square blocks in size.
Redeployment	Alarm rates in company-size areas. In particular, the total alarm rate for those locations that one engine company is closer to than any other engine company (its first-due area); this also applies to ladder companies.
Initial dispatch	The same needs as for redeployment, together with indicators of fire seriousness based on what the dispatcher knows when he decides which companies to dispatch.

We now offer some advice on obtaining these numbers.

DIVIDING THE CITY INTO DEMAND REGIONS

An evaluation of alternative arrangements of fire companies requires considering how they affect different parts of the city, in addition to the citywide total effect. This requires dividing the city into geographical regions. For example, a fire chief would want to compare travel times in the central business district with those in residential areas, where fire protection needs differ.

How are these regions to be defined? Ideally, an individual region would be a geographically compact area of the city, all parts of which have the same land use, type of structure, life hazard, alarm mix, and so forth. That is, it has the same fire protection problems and needs throughout. Locations with different needs would then be in different regions. For the reasons discussed in the next chapter, the regions should also be large enough so that there are several companies in each.

Of course, meeting this ideal is impossible. It is not likely that existing divisions of the city into departmental administrative districts come close to this ideal. An approach that is often successful is to choose several company districts or response areas that have different fire protection needs as "starting points" for the regions. Expand each starting point by adding nearby company districts with similar needs, until every district in the city is assigned to a region. If this result looks satisfactory, stop. It is "satisfactory" if the planner feels that average information about each region will be informative. If, however, one part of a region, say, the north, is thought to have (or desired to have) lower travel times on the average than the south, the result is not satisfactory. In this case, pick a different set of districts as starting points and try again.

We call the resulting regions "demand regions" or "hazard regions." If a meeting is held with chiefs who know each part of the city, and a map of the city is provided for laying out trial regions, the process of defining demand regions should not require more than an hour or so.

IDENTIFYING PARTICULAR HAZARDS

Certain buildings and parcels of land can be identified as hazardous because of the nature of their occupancy. Typical examples would include schools, hospitals, lumberyards, and chemical plants not having their own private fire protection units. In analyzing possible sites for firehouses, the travel times to these hazardous locations will be of special interest.

During the data-collection phase of deployment analysis, the department will want to identify hazardous locations, perhaps distinguishing among degrees of hazard by using different colors on a map (for example, red, orange, and yellow). The Denver case study [14] gives a clear description of how this is accomplished and indicates that fire department officials considered the identification and classification of hazards to be one of the most important and informative parts of the entire analysis.

CHOOSING TIME PERIODS FOR DATA COLLECTION

To answer most of the deployment questions raised in Chapter 1, it is sufficient to consider the demand during the peak hours of the day and/or the peak day of the week or season. Hour-by-hour or week-by-week detail is not necessary. The idea is to capture the significant patterns. For example, in many cities there are wide time-of-day variations (typically, 2.5 times more alarms from 4 p.m. to midnight than from midnight to 8 a.m.) and minor seasonal and day-of-week variations (typically, Friday might have 1.2 times more alarms than Monday, and December might have 1.2 times more than April). The seasonal variation is more pronounced in specific kinds of incidents--for example, brush fires--but it may be reasonable to neglect seasonal and day-of-week differences entirely, especially if the deployment of fire companies cannot be easily changed by season or day of week.

Thus, for data collection purposes it will normally be sufficient to aggregate all demand data into two or three "temporal" categories. For example, one category might be "Friday and Saturday evenings," a second "other evenings," and the third "all other times."

DEFINING TYPES OF ALARMS

Alarm Rate Prediction

To make deployment decisions, it is probably sufficient to distinguish "serious" incidents from all other alarms. What we mean by "serious" incidents are those incidents in which deployment decisions might make a difference in the outcome; that is, if it really matters how long it takes fire companies to get to the scene. According to this definition, false alarms, almost all nonfire emergencies, and rubbish and automobile fires are not serious.*

If a department is planning a careful deployment analysis over a long period of time, it will be worthwhile to decide what types of alarms should be considered serious and to collect data distinguishing serious alarms from others. For example, all fires at which at least two engines and one ladder work might be considered serious, together with certain medical emergencies, or all structural fires at which hoses are used might be considered serious. (Each department will have to decide for itself, because current research is not adequate to specify exactly what kinds of alarms are serious.)

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*Medical emergencies may be serious.

However, for reasonably useful rough estimates to be used in a short deployment study, it will be adequate to consider all structural fires and medical emergencies as serious, or to invent a similar breakdown based on the information available in existing tabulations of alarms.

Work-Time Prediction

To estimate the number of fire companies that are busy (using equation (1)), we are not interested in the seriousness of alarms, but rather in the number of companies that work at alarms and how long they work. For example, false alarms constitute an interesting category for workload prediction because each one consumes little time. They usually constitute a small fraction of the late night alarms in the winter and a large fraction of the early evening alarms in the summer. Therefore, if a department predicts the number of false alarms separately from the number of alarms of other types, its work-time estimates will have the correct pattern: The average company-hours per alarm will be higher for alarms received at 4 a.m. in December than for alarms received at 8 p.m. in July.

For these purposes it will be sufficiently accurate to define three classes of alarms: false alarms, structural fires, and all other incidents. (But there is no penalty, other than additional computation, for defining more classes.)

ESTIMATING ALARM RATES

Whether or not the task of estimating alarm rates presents conceptual or practical difficulties depends on (1) whether the alarms in question are common occurrences, and (2) how the city now collects and aggregates alarm records.

Number of Alarms in Question

When there are many alarms, more or less straightforward use of historical data will give good estimates of alarm rates. For example, to predict citywide *total* alarms next year, look at the citywide totals over the past few years. Average them, or if, as is likely, they have been rising, compute the annual percentage increase for recent years and increase this year's total number of alarms by that percentage. Although this is a rough estimate and may later prove not to have been very accurate, it is satisfactory for deployment analysis.

In contrast, when the alarms in question are not common, it is often necessary to use more sophisticated statistical models and techniques as described in Refs. 5 and 6. For example, suppose that for initial dispatch planning you want to predict the chance that a box alarm[*] from a particular street corner at a particular time is a serious fire. One estimate can be found by dividing last year's citywide total of box alarms into the number of those alarms that were serious. This year-round estimate has some drawbacks, because it ignores the specific location and time of the alarm (both of which are known when the dispatcher makes a decision). In fact, the chance that an alarm signals a serious fire may be very different for different alarm boxes. (See Table 2 for an example from New York City.) It also varies considerably by time of day: There is a much higher chance that a box alarm signals a serious fire if it is received on a cold winter night than if it is received just after school closes.

In light of these comments, it might seem that the seriousness of an incoming alarm could be predicted by considering the history of alarms at the location and the time of its receipt. But many locations have few box alarms and even fewer serious fires in a year. Let us examine what happens when the time period is also restricted, for example, to between midnight and 8 a.m. Then the data might show that Box A had 3 box alarms, none serious, while Box B had 1 box alarm, and it signaled a serious fire. It would not be sensible to conclude that future late night alarms from Box A are surely not serious and those from Box B are surely serious, although that would be the effect of using the historical data without modification.

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[*] The term *box alarm* refers to an alarm received by someone pulling a fire alarm box, as distinguished from an alarm reported by telephone or other means.

There are ways to handle such cases by combining local and city-wide data, but mathematically they are rather complicated. What is needed is a "filtering" of past history through statistical procedures to avoid giving too much weight to recent fires, serious and nonserious, and to account for the possibility of serious fires in situations where they have not occurred before. Before launching an effort to make predictions about infrequent occurrences, a department should be certain it really needs such predictions to answer policy questions. If it does, outside assistance from a statistical consultant will be required to perform the predictions using the methods described in Refs. 5 and 6.

Table 2

STRUCTURAL FIRE PREDICTIONS FOR TWO ALARM BOXES[a]

Bronx Box Number	Predicted Percent Structural (1967-1969 data)	Actual 1970 Data		
			Structural Fires	
		Alarms	Number	Percent
2277	0.4	96	0	0
2209	31.8	94	25	26.6

[a] Using 1967-1969 data, the expected proportion of serious fires was predicted for each alarm box in the Bronx [5,18]. These predictions were compared with actual 1970 data. For example, it was predicted for box 2277 that 0.4 percent of all alarms would be structural fires, while the prediction for box 2209 was 31.8 percent. In 1970, both of these boxes had about the same number of alarms. In both cases, the predictions were quite close to the actual results. Box 2277 had no structural fires, while box 2209 had 25 structural fires. Further, these alarm boxes are only three blocks apart.

The Form of Alarm Records

It should be clear that the kind of statistical tabulations in typical annual department reports to the mayor and city council are not sufficient for analysis of deployment policies. What is required are tabulations of alarm rate and workload statistics by company districts and "demand regions" and by time-of-day periods for different types of alarms. Although this information can be derived by hand computations, it is a tedious process, and the information can be obtained more easily by computer procedures. If information about individual alarms is already keypunched (for example, using a system such as UFIRS[*]), computer programs can be written that will give the department what it needs to use any allocation or redeployment model. If geographic information--nearest alarm box, block number, census tract, company district, or the like--is punched, this process will be straightforward. If not, some ingenuity may be needed to obtain the required information.[†] In addition, geographic information identifying a small area (for example, a box number) rather than a large one (for example, a company district) is important for analyzing the siting of firehouses and initial dispatch policies.

If information for each alarm is not keypunched routinely, it will help in future deployment analyses to record at least one year's incident information on coding forms, such as the one shown in Fig. 4. For current analysis, coding and keypunching past incidents may be preferable to hand computations. The data can then be punched from the coding forms. This was done in the Institute's deployment studies conducted in Trenton, Yonkers, Wilmington, and Jersey City. (See, for example, Ref. 12, pp. 12-17.)

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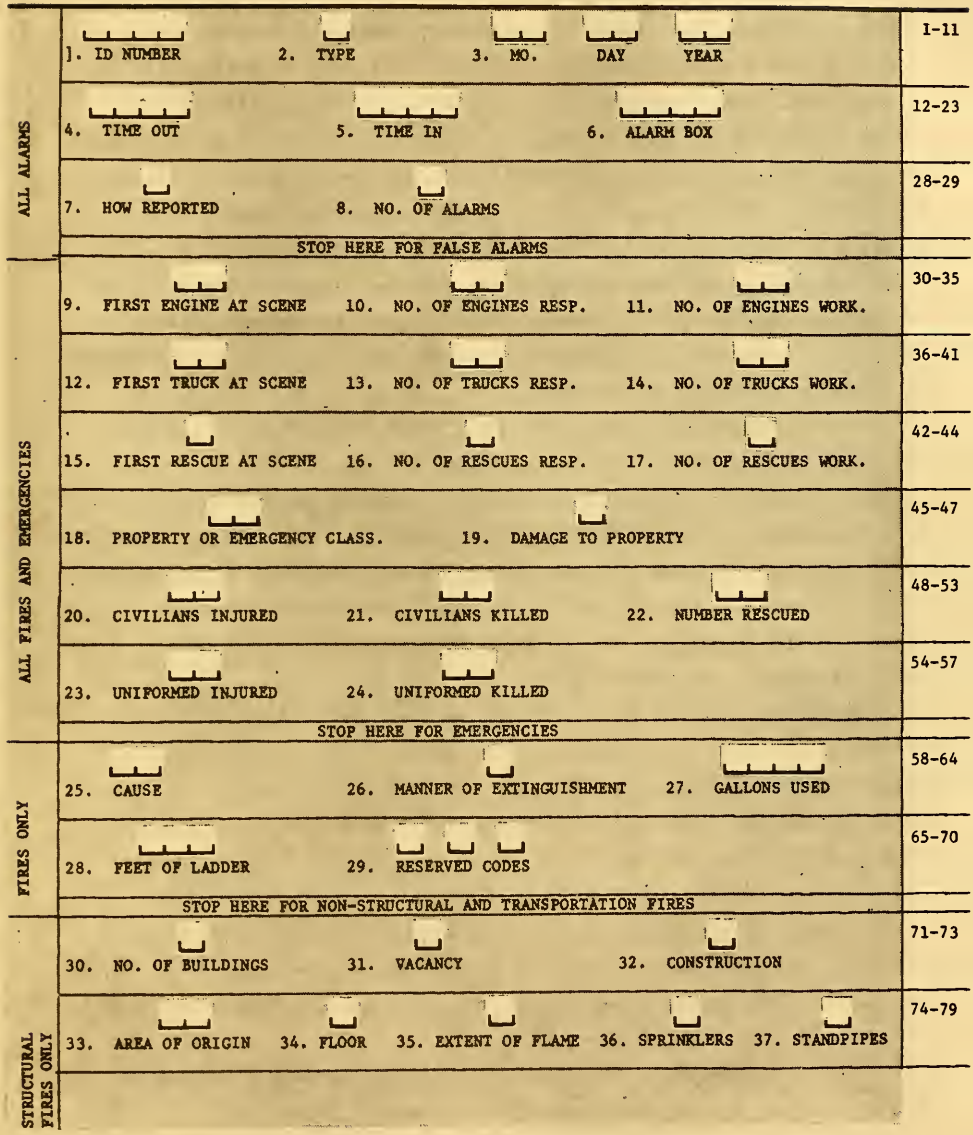
[*] The Uniform Fire Incident Reporting System [31] developed by the National Fire Protection Association.

[†] If addresses are recorded and keypunched, computerized address-matching procedures can be used. But this is more difficult than one might guess, and some 20 percent of addresses usually fail to match due to misspelling of street names, special locations identified by name rather than address (for example, City Hall), and incomplete address-matching files.

FIRE INCIDENCE REPORT FORM



ALL ALARMS	1. ID NUMBER	2. TYPE	3. MO.	DAY	YEAR	1-11
	4. TIME OUT	5. TIME IN	6. ALARM BOX			12-23
	7. HOW REPORTED	8. NO. OF ALARMS				28-29
	STOP HERE FOR FALSE ALARMS					
ALL FIRES AND EMERGENCIES	9. FIRST ENGINE AT SCENE	10. NO. OF ENGINES RESP.	11. NO. OF ENGINES WORK.			30-35
	12. FIRST TRUCK AT SCENE	13. NO. OF TRUCKS RESP.	14. NO. OF TRUCKS WORK.			36-41
	15. FIRST RESCUE AT SCENE	16. NO. OF RESCUES RESP.	17. NO. OF RESCUES WORK.			42-44
	18. PROPERTY OR EMERGENCY CLASS.	19. DAMAGE TO PROPERTY				45-47
	20. CIVILIANS INJURED	21. CIVILIANS KILLED	22. NUMBER RESCUED			48-53
	23. UNIFORMED INJURED	24. UNIFORMED KILLED				54-57
	STOP HERE FOR EMERGENCIES					
FIRES ONLY	25. CAUSE	26. MANNER OF EXTINGUISHMENT	27. GALLONS USED			58-64
	28. FEET OF LADDER	29. RESERVED CODES				65-70
	STOP HERE FOR NON-STRUCTURAL AND TRANSPORTATION FIRES					
STRUCTURAL FIRES ONLY	30. NO. OF BUILDINGS	31. VACANCY	32. CONSTRUCTION			71-73
	33. AREA OF ORIGIN	34. FLOOR	35. EXTENT OF FLAME	36. SPRINKLERS	37. STANDPIPES	74-79

Fig. 4—A sample coding form for collecting fire incidence data

ESTIMATING WORK TIMES

In the previous section we discussed ways of obtaining statistics on alarm rates. To estimate the average number of companies busy in a region during a time period using equation (1), the average number of company-hours per alarm must also be known. First, it is useful to get a year-round citywide average. This is usually not difficult, because in most cities fire companies report monthly and yearly total work time at all incidents. To calculate the average engine company-hours per alarm, simply add the recorded annual work times for each engine company and divide by the total number of alarms in the city.* (If travel time is not included in work time, adjust accordingly. Adding, say, 5 minutes for every company response is sufficiently accurate to analyze deployment policies.)

The average calculated in this way gives the number of company-hours for an average alarm without regard to time of day, season, or region of the city. Consequently, as we indicated before, the average is too high for use in situations where false alarms predominate (compared with the citywide figure) and too low when there are relatively more structural fires. To adjust the average, consider both how long companies spend at different types of incidents and what fraction of the incidents are of each type.

The fraction of each type can be obtained from the alarm rate estimates. For example, suppose in a particular demand region the predictions are 1.2 structural fires per hour, 1.0 false alarms per hour, and 1.8 "other" alarms per hour, for a total of 4 alarms per hour. Then, the fraction structural is .3 = 1.2/4, the fraction false is .25 = 1.0/4, and the fraction "other" is .45 = 1.8/4.

A reasonable estimate of how long companies spend at these three types of incidents is not difficult to determine. Because these times are unlikely to change significantly from company to company or with time of day, citywide figures can be used.

If fire companies routinely report monthly or yearly responses and work times not only in total but separately for each type of alarm, these numbers can be used directly. For each alarm type, add the work times for the different companies (times for engines and ladders should be added separately) and divide by the citywide total number of alarms of that type.

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*Do not divide by the total number of engine company responses.

If such routine reports are not kept by alarm type, take a small sample from company journals, dispatcher's logs, and chief officer's reports. For example, find the chief's reports on, say, 20 recent structural fires. Check the journal of each company mentioned in the report and find how long it worked. Add all the work times and divide by the number of fires in the sample (in this case, 20) to give the average company-hours per structural fire. Repeat the process for false alarms and other alarms.

With this information it is possible to obtain the average number of engine company-hours per alarm that is appropriate for a particular time of day and region. Use the citywide average number of company-hours for each type of alarm, together with the fraction of incidents of that type in the time period or region of interest. Multiply these together and sum to form a weighted average as follows:

$$\begin{aligned}\begin{pmatrix}\text{Average engine}\\ \text{company-hours}\\ \text{per alarm}\end{pmatrix} &= \begin{pmatrix}\text{fraction of}\\ \text{incidents that}\\ \text{are structural}\\ \text{fires}\end{pmatrix} \times \begin{pmatrix}\text{average engine}\\ \text{company-hours}\\ \text{per structural}\\ \text{fire}\end{pmatrix}\\[1ex] &+ \begin{pmatrix}\text{fraction of}\\ \text{incidents that}\\ \text{are false}\\ \text{alarms}\end{pmatrix} \times \begin{pmatrix}\text{average engine}\\ \text{company-hours}\\ \text{per false}\\ \text{alarm}\end{pmatrix}\\[1ex] &+ \begin{pmatrix}\text{fraction of}\\ \text{incidents that}\\ \text{are "other"}\end{pmatrix} \times \begin{pmatrix}\text{average engine}\\ \text{company-hours}\\ \text{per "other" alarm}\end{pmatrix} .\end{aligned}$$

For example, suppose that (by one procedure or another) the following estimates of engine company-hours per alarm were obtained: structural fires, 1.5; false alarms, .2 (= 12 minutes); and "other" alarms, .4. Also suppose that .3 of the incidents in the region at that time are structural, .25 are false, and .45 are "other." The average engine company-hours per alarm would be (.3 × 1.0) + (.25 × .2) + (.45 × .4) = .59 hours.

ESTIMATING TRAVEL-TIME AND TRAVEL-DISTANCE RELATIONSHIPS

The square-root law and the travel-time relationship described in equations (4) and (5) relate travel distance to the average number of companies available in a region and relate travel time to travel distance. Both equations have constants that vary from city to city. A fire department can find out the "right" constants for its city, but as we have already pointed out this is not necessary. The reason that a department can use the constants we gave for other cities is that the meaning of a travel-time calculation for *policy* purposes is not much affected by small changes in the constants.

For example, suppose a fire department uses the constants we gave when describing the equations in Chapter 2 and finds that moving Engine Company No. 3 to Front Street will reduce average travel time downtown by 10 seconds. Then suppose it calculates the "right" constants for its city and finds that moving Engine Company No. 3 to Front Street will reduce average travel time downtown by 9 seconds. The policy implication has not changed--namely, the average will decrease, but not by very much.

Despite this observation, many planners and fire chiefs do not feel comfortable making decisions based on travel-time relationships from other cities. If this is the case, it is possible to collect data to obtain the "right" constants in your city. The fire companies have to record travel times (using stopwatches) and odometer readings, using procedures and data forms described in Ref. 11. This reference also lists a computer program that calculates the "right" constants from the data collected by the fire companies.

Chapter 4

LOCATING FIRE STATIONS

The present arrangement of fire company locations in different parts of many U.S. cities is more the product of historical factors than the result of a plan to meet current needs. In the oldest part of town, the spacing among fire stations reflects where volunteer companies were located or required in the days of horse-drawn vehicles, while in successively newer parts of town the spacing reflects gradually changing requirements of the Standard Grading Schedule of the National Board of Fire Underwriters and its successor, the Insurance Services Office (ISO) of the American Insurance Association. In this chapter we discuss some recently developed methods that can be used to help determine the total number of fire companies a department should have on duty, how they should be allocated to various regions, and where the firehouses should be located. These are the three strategic deployment issues mentioned in the Introduction.

THE NUMBER OF FIRE COMPANIES

An economist would say that in theory there is no difficulty in determining the number of fire companies a city should have. A cost benefit approach can be used. A city should add fire companies as long as the improvement in fire protection from adding one more company (the marginal benefit) is more than the cost of adding the company (the marginal cost).

The problem with this approach is that, although it is clear that the number of fire fatalities and the amount of property loss depend on the time it takes fire companies to reach fires, researchers have been unable to estimate the relationship accurately enough for it to be of use in determining the number of fire companies a city should have. In addition, the relationship is probably a function of many different variables (types of housing, population at risk, etc.), so that even if the relationship could be determined for one area of a city, it would be unlikely to apply to other areas of the same city, much less to other cities. In addition, to compare costs with benefits, a monetary value must be placed on human life. Although one can argue that city decisionmakers do this implicitly when making budgetary decisions, it would be difficult for them to do so explicitly.

Researchers are developing models for relating fire losses to travel time. This work is very interesting, but still must be considered speculative. For example, Hogg [15] has developed relationships for the United Kingdom as a whole. But whether it is safe to apply the results from her aggregate data to individual communities has not yet been established. Further, her model does not lend itself to statistical verification.

There are few other useful guides to help officials determine the level of fire protection that should be provided in their cities. The Grading Schedule published for national use by the ISO suggests maximum travel distances for engine companies and ladder companies [10]. These guidelines are based on the estimated fire flow (gallons of water per minute) required for different buildings, on a knowledge of the number of gallons per minute each engine company can deliver, and, implicitly, on judgments of the response times needed to ensure timely delivery of the water required. For truck companies, the guidelines are apparently based on judgments of fire risks as determined by the ISO. These standards were developed as a means of classifying municipalities to determine fire insurance rates, with emphasis on the prevention of conflagrations.

To determine the number of companies a city will need and their locations, we have taken a different approach from the ISO because its standards do not have the strong scientific or empirical foundations of standards in other fields. We have preferred to ask fire officials to look directly at the travel distances and times implied by different allocations of companies, rather than to rely on whether the allocations meet ISO (or any other preset) standards. Our approach is practical and easy to apply, and it has been tested in a number of cities.

In most of the cities where we have worked, the firehouse location problem hinges on the fire department's budget level--the city has x number of dollars to spend in the fire department. Given this figure, we ask how many companies should it have and where should they be located? The budget level determines the number of firemen on the payroll and, for a specified company manning level, the number of men determines the number of fire companies that can be deployed.

Our analysis next concentrates on determining the best allocation of this fixed amount of resources. Mathematical models are used to predict the values of a large number of performance measures that would result from various arrangements of fire companies. Then the assumed department budget level is varied, and the analysis is repeated. After looking at the results for several different budget levels, the decision-maker can compare costs and benefits to choose the best policy for his city, taking into account factors that are not directly considered by the models, such as political constraints.

The methodology developed at The New York City-Rand Institute divides the analysis of deployment alternatives for a fixed budget level into two stages. First, the best way is found to allocate the given number of fire companies to regions of the city. Then specific sites are found for each of the companies. There are two reasons for performing the analysis in two stages. First, in any city with more than 10 engine or ladder companies, there are a large number of possible ways to arrange the companies. Considering them all would be very costly. Allocating the companies to regions at the beginning of the study reduces the number of alternative arrangements to be evaluated. Second, the allocation stage gives the department a quick and inexpensive estimate of the improvement in fire protection that can be expected if the locations of the city's fire companies were changed.

THE ALLOCATION OF FIRE COMPANIES

Even if it were possible to determine analytically the number of fire companies that should be deployed in a city, it is still not clear how they should be distributed throughout the city. The problem is caused by variations in alarm rates and fire hazards in a city, and by the conflicting objectives of a fire department. A fire department would like to be able to concentrate its companies in the areas of greatest demand. However, the department must also provide a reasonable level of service to the lower demand areas.

How may these objectives conflict? Consider the hypothetical city shown in Fig. 5, which has been partitioned into two regions of about equal size but with very different fire alarm experiences. One region has many fire alarms, the other a very few. How should the city's 10 fire companies be allocated between the two regions?

Suppose that travel time is being used to measure the quality of fire protection being provided. One objective of the fire department might be to minimize the total travel time to all fires that occur in the city. In this case, the companies should be placed close to where the fires are expected to occur. As a result, eight companies would be allocated to the high-demand region and only two to the other region.

A problem with this solution is that when a fire does occur in the low-demand region, it may take a very long time for the fire companies to arrive. Residents in the low-demand region might claim that they are receiving substandard protection and are being penalized for being careful and having few actual fires. Minimizing travel times to actual fires also ignores the potentially high fire hazards or special dangers that may be present in the low-demand region, for example, hospitals, schools, chemical storage areas, nursing homes, etc.

An alternative objective is to locate the fire companies so that the average travel time to alarms is made equal in the two regions. Using this objective, the number of companies would be almost the same in both regions. This may seem to be a more equitable solution. But, as a result, the travel time to many fires in the high-incidence region will be increased to reduce those to the few fires of the low-incidence region. Moreover, the average travel time throughout the city will be larger than the minimum possible. Under this policy, therefore, total fire losses in the city would presumably be greater than under the minimum travel-time policy because many fires would be getting slower responses. In addition, the companies in the high-incidence region would have a higher workload than the companies in the low-incidence region, an important consideration in some cities. Equalizing travel times in all regions of a city also fails to take into account differing levels of demand in different regions; it results in the same travel time in high-hazard, high-alarm-rate areas as in low-hazard, low-alarm-rate areas.

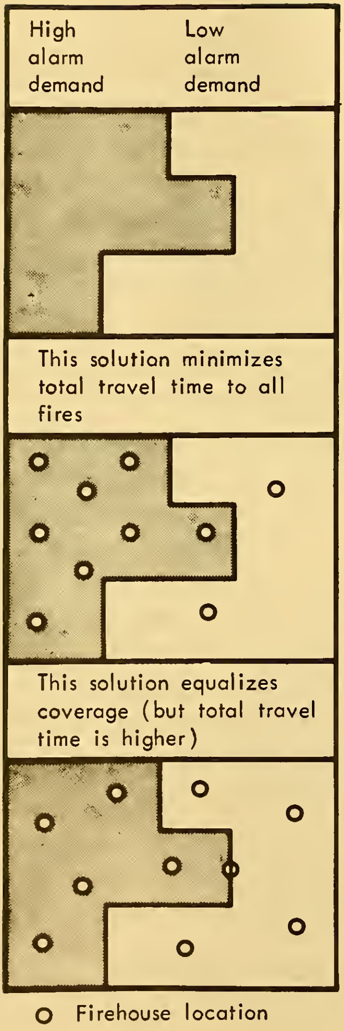
High alarm demand
Low alarm demand
This solution minimizes total travel time to all fires
This solution equalizes coverage (but total travel time is higher)
○ Firehouse location

Fig. 5—Conflicting objectives in the placement of firehouses

Neither of these allocations is likely to be acceptable. In practice, departments make allocations that are compromises between these two extremes by placing more fire companies in high-demand regions, but still making sure that all regions receive an acceptable level of coverage. A model called the Parametric Allocation Model [25] (also known as the allocation model) can be used to examine the consequences of allocations that result from a wide range of compromises.

The allocation model operates according to the principles outlined in Chapter 2. It estimates average travel distances in a region using the square-root law, and translates travel distances into travel times using a function like the one shown in Chapter 2. To use the allocation model, the city must be divided into demand regions, as described in Chapter 3. The allocation model will determine the number of fire companies that should be located in each of these regions.

The regions must be relatively large (containing at least two or three fire companies of each type being allocated), and should be relatively homogeneous with respect to demands for fire-fighting services. There are two types of demands that must be considered in determining suitable allocations. First is the demand that comes from the occurrence of actual fires (realized demand). The other is the demand that comes from the existence of fire hazards to life and property (potential demand). The fire department must have units stationed close to such hazards, even if they will rarely have to respond to fires there.

To use the allocation model, we need to provide only a very limited amount of data for each demand region:

- Average alarm rates for various types of alarms for the busiest hours of the day.
- Area of the region.
- Existing number of engines and ladders in the region.
- A subjective measure of the hazard in the region (potential for loss of life or property if a fire does occur).

In addition, certain citywide data are required, including the parameters needed to estimate travel distances and travel times, and work times for the fire companies at each type of alarm.

Using this information, the allocation model estimates the following performance measures for each demand region:

- Average first- and second-due travel times.
- Average first-due response distance.
- Average number of companies busy.
- Average number of companies busy per square mile.

The allocation model can be used in two ways: to evaluate (display these performance measures for) an allocation proposed by the user, or to determine the best allocation of companies to regions for a given value of a *trade-off parameter*.*

A typical application of the Parametric Allocation Model might involve running the computer program several times. First, the model is used to calculate the travel-time and workload characteristics of the existing allocation. This might show that the travel times in one region are unacceptably high as compared with the travel times in other regions. The model can then be used to generate allocations for several values of the trade-off parameter. Fire department personnel can then compare the workloads and travel times, citywide and in different regions, that would result from the various allocations. Based on these results, the department can decide which allocation of fire companies to regions of the city would be most desirable.

If the user considers that the level of fire-fighting resources in the city is too low or too high (or if he wants to see the effect of adding or eliminating companies), the model can be used to evaluate the travel-time and workload characteristics of allocations with various total numbers of fire companies. The results will indicate the regions that should gain or lose companies.

The general procedure for using the allocation model is shown in Fig. 6.

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*This parameter describes how much emphasis is to be given to *minimizing* travel time and how much to *equalizing* travel time.

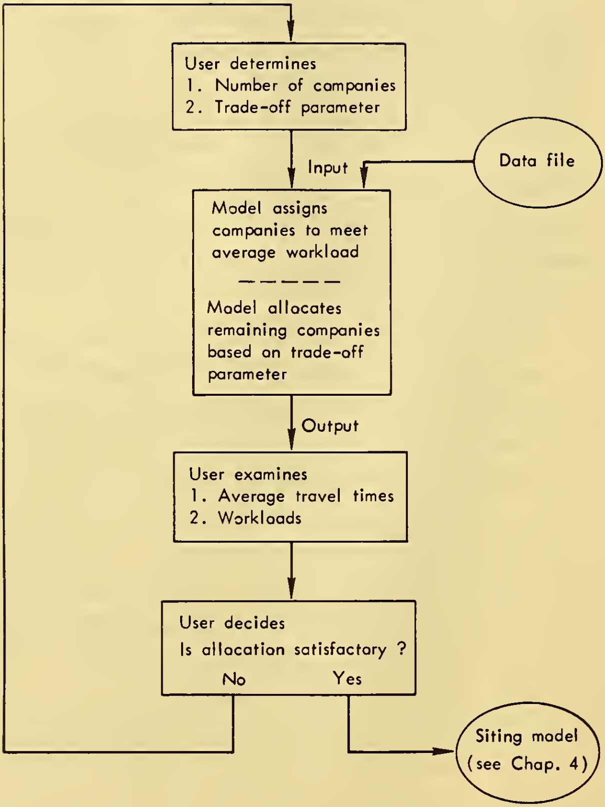
User determines
1. Number of companies
2. Trade-off parameter
Input
Data file
Model assigns companies to meet average workload
Model allocates remaining companies based on trade-off parameter
Output
User examines
1. Average travel times
2. Workloads
User decides
Is allocation satisfactory ?
No
Yes
Siting model (see Chap. 4)

Fig. 6—Steps in the use of the Parametric Allocation Model

THE LOCATION OF FIRE STATIONS

The allocation model provides a general picture of the number of fire companies that should be deployed in different parts of a city. It is simple and easy to use and requires very little data. But it cannot be used to determine specific locations for firehouses.

However, once a fire department has chosen (at least tentatively) the number of companies to be assigned to each region of the city, it can develop several alternative configurations of station sites that might lead to desired levels of performance. In small communities the planner will have no difficulty choosing the best alternative when he studies maps displaying the various possible arrangements. However, in larger cities it is nearly impossible to look at a map and make accurate "guesses" regarding the workloads of the units or areas where travel times will be too high.

Recently, several computer programs have been developed to help the planner evaluate alternative arrangements of fire companies. The programs show what will happen to travel times and company workloads if a given arrangement of fire companies is used. By comparing the results from one arrangement with those from others, fire department managers can make good choices for the locations of fire companies. Although these models do not suggest arrangements to be tried, our experience indicates that examination of their output makes it easy to eliminate poor arrangements and to pinpoint good arrangements.

The three principal programs of this type that have been applied to the problem of locating firehouses are the Firehouse Site Evaluation Model of The New York City-Rand Institute [7,32], the Fire Station Location Package of Public Technology, Inc. (PTI) [24], and the Station Configuration Information Model (SCIM) of the Denver Urban Observatory (Ref. 14, pp. 44-45).* The three programs share several common features. In each case, the city must be divided into small *subareas*, as small as the area covered by a single alarm box or an area up to four or five times this size. The subareas must be reasonably small, because the models assume that the demand for fire service in a subarea arises at only one point, and that the travel times to any place in the subarea will be the same as to that point. In addition, all three programs permit the user to identify some subareas that have special hazards, to which the analysis can pay special attention.

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Estimating Travel Times

The three models differ primarily in the method used to estimate travel times and in whether or not alarm incidence is used in calculating some of the performance measures. In the SCIM, the travel time between each candidate firehouse site and each subarea is input to the model, and therefore any method can be used to calculate travel times. The two methods used in the other two models are summarized in Table 3.

In the PTI approach, a street map of the city is converted into a computer-readable network description in which street intersections are represented as nodes and streets are the connecting links between the nodes. An estimate is made of the average speed at which a fire company would travel along each link, which is then used to obtain an estimate of the average travel time along the link. The expected travel time from any firehouse (a node in the network) to any subarea (another node) is then estimated by finding the set of links that form the shortest time path.

The Institute's approach is to assign grid coordinates to every potential station site and subarea. The travel distance is then estimated by assuming that the fire companies travel on streets that parallel the grid.* Finally, the travel distance is converted into travel time using equation (5) in Chapter 2. (This is the equation that is illustrated in Fig. 2.) In some cities, grid coordinates have been determined by overlaying a transparent sheet of graph paper on a map showing the station sites and the centers of subareas (usually each of these is the location of an alarm box) and recording the closest x and y coordinates

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*At user option, the Institute's siting model will estimate travel distances as a constant times the straight-line distance. Neither of the two estimation procedures in the siting model is intended to imitate the path followed by fire companies.

Table 3

TWO METHODS FOR ESTIMATING TRAVEL TIMES

Steps in the Method	Advantages of the Method
Method Developed by PTI (Public Technology, Inc., Ref. 24)	
Describe street network of city in computer-readable form. Street intersections are identified as nodes in the network, streets are represented as connecting links between nodes. Not necessary to consider all streets; main arterials are adequate. Estimate average travel speed on each link. This may be done from experienced guesses, traffic surveys, experimental trips by fire companies, or from previously collected response-time data. Scale distance for each link off a map of the community. A computer program estimates time to travel over each link using speed and distance. Subareas are called fire demand zones; the point representing all the properties in a fire demand zone is called a focal point. Every potential or existing firehouse and every focal point is referenced to a node of the street network. The program estimates the travel time from a firehouse to a focal point by finding the set of connecting arcs that form the minimum time path.	If road network has already been developed (by traffic department, for example), this is fastest way to proceed. Road network, when developed, may be useful to other city agencies in locating other public services. Barriers to travel (hills, railroad tracks, rivers, airports) are automatically taken into account. Effects of changes in structure of road network can be analyzed in advance (new interstate highway, new bridge, closing of existing bridge). Irregularly shaped areas (peninsulas, or cities with holes in them, for example) are automatically handled accurately. Fire officials may feel more comfortable with a method that actually imitates the path followed by fire companies.
Method Developed by the Institute (New York City-Rand)	
Determine x-y coordinates of subareas and existing and potential station sites from a grid map of the city. Determine parameters a, b, c, and d to convert travel distance to travel time (equation (5)) by running a "travel-time experiment" (Ref. 11). Program estimates travel distance as "right-angle distance" or modification of straight-line distance (Ref. 7). Program converts travel distance to travel time using equation (5).	Elaborate data base and computer program not needed to prepare input for the siting model; lower cost for analysis. If road network has not already been developed, this method is significantly faster. If travel times have already been collected (for example, by UFIRS), this method is very fast. Parameters a, b, c, and d have been so close to the same values for many cities that it may be possible to proceed without collecting any travel-time data.

for each one. (Accuracy to several hundred feet has been considered adequate.) In other cities, a commercial service bureau provided grid coordinates accurate to a few feet at a cost of approximately 10 cents for each subarea. Planners might also wish to check whether their city or county traffic department already has grid coordinates for every intersection. However it is accomplished, the preparation of all required grid coordinates is only a few days' work.

Because the travel-time estimates produced by the PTI and the Institute approaches have never been directly compared, it is not possible to say which approach will produce the best estimates. However, certain aspects of the two approaches would make one or the other preferable in certain circumstances. For example, construction of the computer-readable road network required by the PTI approach is a time-consuming task. (See Ref. 24 for a detailed description of the resources required.) The Institute's approach does not require such an elaborate data base; nor does it require the computer program to calculate the shortest time paths between two points. Thus, if a computer-readable road network of the city has not already been developed, the Institute's method is the fastest and lowest in cost. However, if a road network has already been developed, PTI's approach is the fastest.

The PTI approach is also to be preferred if the city contains a large number of barriers to travel (impassable hills, railroad tracks, rivers, airports), or irregularly shaped areas (peninsulas). In these cases, it will be difficult, using the Institute's approach, to produce accurate estimates of travel distances. In addition, officials may feel more comfortable with the PTI estimates because its calculations actually imitate the path followed by fire companies, and the network, once developed, can be used for other purposes. However, the Institute's approach has been validated against actual travel-time data in several cities and has been found to be quite accurate in those cases (more than enough for firehouse site selection purposes).

Output from the Models

All three of the firehouse siting programs calculate a set of similar descriptive measures for a given arrangement of fire companies, concentrating on the travel times of fire companies to subareas. All are based on the same two assumptions:

1. Units are always available in their firehouses to respond to an incoming alarm. (This is a reasonable assumption for most cities. The travel-time estimates produced by these models will be useful for making deployment decisions as long as the average fire company is available at least 90 percent of the time.)
2. The closest units are always dispatched to an alarm.

All programs perform separate calculations for ladder companies and engine companies.

There are, however, some important differences in the specific output measures calculated by the programs. Because the SCIM and the PTI models have very similar output, and the PTI model is better documented, more easily available, and more widely used, we will concentrate on the output from the PTI model. The subareas in this model are called *fire demand zones*. The point representing all the properties in a fire demand zone is called a *focal point*. For each demand zone, a required travel time for the closest unit is specified, as well as the number of alarms that occurred within the zone during some selected time period.

After receiving specifications of a firehouse configuration, the PTI program estimates the resulting travel times between firehouses and fire demand zones (actually between firehouses and focal points). The output shows the fire demand zones that are uncovered (estimated travel time of the closest unit is greater than a specified maximum travel time), the frequency distribution of first-due travel times to demand zones (that is, the number of zones with travel times less than one minute, between one and two minutes, etc.), the average travel time to covered zones, and the overall average travel time. Another output report displays the demand zones in each fire company's first-due area, and shows the estimated travel times of the first-, second-, and third-due units to each demand zone.

The Institute's Firehouse Site Evaluation Model (also called the "siting model") uses the term *alarm box* to refer to a subarea. The model requires that the user assign grid locations to every alarm box and firehouse in the city. To facilitate the evaluation of alternative arrangements of fire companies, each alarm box may be assigned to a demand region. The use of demand regions makes it possible to compare fire protection in regions of the city that have similar demand characteristics to see if imbalances exist. It also makes it easy to see whether the more hazardous regions have smaller travel times. (In the PTI approach, the user may specify in advance faster travel-time requirements for the more hazardous locations and determine whether they are met.)

Because one configuration of firehouses will rarely result in travel times that are superior to those of another configuration for every alarm box, the siting model provides information on travel times to groups of alarm boxes. The boxes are grouped in several ways:

- *Citywide.* Aggregate results are printed for the city as a whole.
- *By demand region.* Results are printed separately for each of the previously defined demand regions constituting the city.
- *By company response area.* The boxes responded to by each company are aggregated and summary statistics are printed.
- *By the boxes to which travel times are affected by the rearrangement of companies.* In any use of the model, results are presented for two configurations of companies: a previously defined configuration, called "current," and the new one under consideration, called "proposed." The "affected region" is the set of boxes to which travel times are different in the current and proposed configurations.
- *By all boxes that represent special hazards.* Travel times are printed for each of these special "target" hazards and summarized for the whole group.

For each of the above groups of alarm boxes (except company response areas), the siting model provides the values of the following performance measures for both the "current" and "proposed" configurations:

- Average travel time to an alarm box (giving equal weight to each box).
- Average travel distance to an alarm box.
- Average travel time to a structural fire (taking into account that some alarm boxes have more structural fires than others).
- Average travel distance to a structural fire.
- Maximum travel time to any box in the group.

All of the above statistics are calculated separately for engine companies and ladder companies, and can be obtained for first-due, second-due, third-due, etc. responses, up to the response level requested by the user. (The only aggregate travel times provided by the PTI model are the average first-due travel time citywide, and the average first-, second-, and third-due travel times in each company's first-due area.)

In addition, the output for each demand region, and the citywide output as well, includes a report that shows the number of alarm boxes whose travel time under the proposed configuration falls into each of a number of half-minute intervals. This can be used to see how frequently very long travel times occur using a particular configuration of companies. The output from the PTI model includes a similar report showing the distribution of first-due travel times to fire demand zones citywide.

Finally, for each company's response area (both current and proposed), the siting model program prints the number of boxes in the area, the average and maximum travel times, and the alarm rates in the area. The alarm rates provide an estimate of the workload of the fire companies. These can be used to determine whether a proposed configuration of firehouses will result in too much work for a particular fire-fighting unit or large workload imbalances among the units.

Applications

There are many ways to use this information to evaluate alternative arrangements of fire companies. For example, if the department is considering eliminating a particular company, the first-due travel time will necessarily increase in the region where the company is now first due (this is the "affected region" for the proposed configuration). Using data from the siting model, two measures of the change in fire protection can be calculated: (1) the increase in first-due travel time in the affected region multiplied by the number of alarm boxes in the region (a measure of the loss in coverage--see the definition of measures in Chapter 1), and (2) the difference between the average first-due travel time to structural fires under the existing and proposed configurations (the increase in travel time to structural fires).

To make most effective use of any program's output, the department's planners would identify and summarize important results so that the relative rankings of the various arrangements of fire companies could be assessed. In some cases, a trial configuration may prove to be obviously unacceptable. For example, two demand regions that have approximately the same fire hazards and demands might be found to have very different travel times. A new trial configuration would then be designed, and the siting model would be used to determine whether an adequate improvement has been made. It is unlikely that the siting model's results for several configurations will produce a particular arrangement that is obviously the best. For example, one configuration might improve travel times in the downtown area while degrading them in outlying areas, while another might have the opposite effect. Ultimately, an administrator who understands the entire operational and political context of the department must decide which of the arrangements studied appears best, all things considered, or whether still more arrangements should be analyzed.

Case studies showing the step-by-step process by which the siting model was used to determine and evaluate new arrangements of fire companies in Trenton, Jersey City, Yonkers, and Wilmington are contained in Refs. 12, 13, 26, and 33. PTI's Fire Station Location Package has been used in over 60 jurisdictions, but no published case studies are available at this time.

The PTI model has a capability that the Institute's model does not have. It can be used to find the minimum number of firehouse locations needed so that first-due travel time to each demand zone is no more than a specified minimum. However, some early structural and computational problems with this approach resulted in little emphasis being placed on this use of the model in the current documentation. Because this approach does show promise, we hope that future versions of the documentation will include it.

To date there has been no comprehensive comparison of the various models for locating fire stations or of jurisdictions that have used them. In this brief description we have provided comparisons of selected technical aspects of the models. The potential user, however, should consider not only these aspects of the models but also the policy and management issues inherent in undertaking a program to analyze station locations and implement the results. The reports on the Fire Station Location Package [24] include a step-by-step guide to organizing, managing, and implementing the analysis as well as forms for collecting and organizing data required by the model. Planners considering an analysis of fire station locations should review all the references cited in this chapter before deciding which approach appears most satisfactory for their own department.

Chapter 5

REDEPLOYMENT

When one large fire, or several small fires, are being fought in a single area of a city, the firehouses of the working fire units are left empty, resulting in a sharp degradation in the fire protection afforded the surrounding area. Many cities relieve this situation by relocating companies into some of the empty houses in the affected area.

Most cities have preplanned their relocation assignments. These methods are adequate at low alarm rates but break down at high alarm rates. Typical problems at high alarm rates are:

- The companies designated to move may be unavailable, so the plan cannot be implemented.
- The designated companies may be available but moving them would create new, and possibly worse, gaps in coverage due to the unavailability of neighboring companies.
- Several simultaneous small fires in the same area may create a need for relocations that is not recognized by the advance plans, which consider only one major fire at a time.

A computer-based procedure [21] was developed at The New York City-Rand Institute for making relocation decisions dynamically, based on up-to-the-minute information about the status of fire companies. Some parts of this procedure can be used to generate preplanned relocations for those cities in which such relocations present no problems.

The Institute's procedure separates these relocation problems into four subproblems, which are solved sequentially:

1. When should relocations be made?
2. How many companies should be relocated?
3. Which companies should be relocated?
4. Which vacant house should each of the relocating companies fill?

The calculations and redeployment analyses are performed separately for engine companies and ladder companies.

1. *When should relocations be made?* A call for relocations is made whenever the fire protection being provided in any area of the city falls below some minimum level. The minimum standards that the Institute developed for New York City are based on maintaining the *relative* densities of fire companies throughout the city rather than on specifying maximum travel-time or travel-distance standards for every area of the city. Relocations are made whenever some location in the city has both its first-due and second-due companies (ladders or engines) unavailable, and they are expected to be unavailable for some extended period of time. Such a location is said to be *uncovered.*

2. *How many companies should be relocated?* Enough vacant houses should be filled to ensure that no location remains uncovered, while moving as few companies as possible.

3. *Which companies should be relocated?* Four general principles govern the choice of which companies to relocate:

- A company should not be moved if by so doing new locations will become uncovered.
- A company should not be moved if it is "too busy." A busy company is more likely to have an alarm occur in its area while it is relocated than is a less busy company. If its house is empty, a substitute company will have to respond from farther away.
- A company should not be moved if it is protecting "too large" a region. If such a company is moved and an alarm occurs in its area while it is away, the resulting travel time for the substitute company will be too long.
- A company should not be moved "too far." A company that is relocated a long distance will spend too much time traveling and will, therefore, be out of its area longer than if a closer company were moved. The long relocation time increases the chance that an alarm will occur in its area while it is away, resulting in long travel times to the alarm.

We have used a single number to measure the "cost" of a particular relocation plan. This cost is the average first-due travel time to alarms that are expected to occur in the area affected by the moves during the duration of the moves. It takes into account whether a company is "too busy" by including the alarm rate in its first-due area. It estimates whether it is protecting "too large" a region by including the size of its first-due area. And it takes into account whether the company will have to go "too far" by including the travel time between its present location and the location of the vacant house it would be filling.

The relocation procedure, then, is to select those available companies to move that will produce the lowest "cost" without uncovering any of their home areas.

4. *Which vacant house should each of the relocating companies fill?* Step 2 chooses the set of houses to be filled. Step 3 chooses the set of companies to be moved. It also specifies how the companies should be assigned to the vacant houses to obtain the smallest "cost." However, it has been found that the assignments produced in step 3 can be improved by applying a further objective--minimizing the time that the relocating companies will spend traveling.

There are several reasons why fire departments would want to do this. First, shorter relocation times are less of a burden on the relocating companies and increase their availability. Second, moving companies shorter distances tends to keep them in areas in which they are familiar with the street patterns as well as with the fire-fighting problems.

Of course, modifying the relocations suggested in step 3 would not make sense if it resulted in relocations whose "costs" were significantly higher. But tests performed by researchers at the Institute indicated that, in most cases, the relocation cost would be increased very little, while the total travel time of the relocating companies would be reduced significantly (Ref. 21, p. 25).

* * *

An on-line computer program has been written that implements this algorithm. The program, documented in Ref. 28, has been used to test the algorithm and to analyze its recommendations before the algorithm is incorporated into the New York City Fire Department's computer-based Management Information and Control System. As mentioned before, this program, although designed to be used in a real-time system, can also be used to generate relocations for use in a manual, preplanned system.

Chapter 6

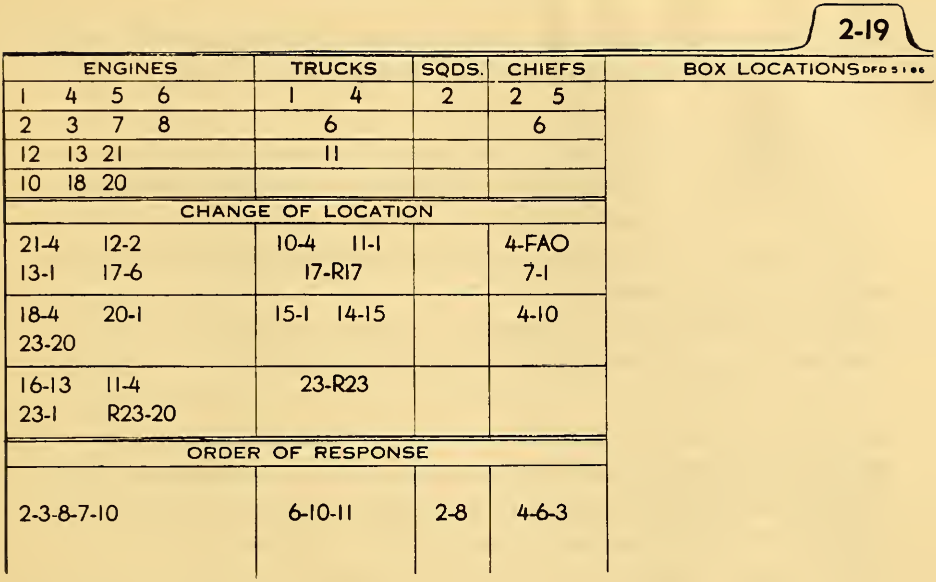
INITIAL DISPATCH

How many companies should be sent to a new alarm? Which ones should be sent? In most cities, the number sent is determined by how the alarm was reported, the location within the city, and, if it is by telephone (or the equivalent), by the apparent nature of the incident. With few exceptions, the companies closest to the incident are dispatched.

What improvements, if any, are possible in these procedures? Do the required fire-fighting units reach the serious fires quickly without burdening the men with needless responses? Several models have shown that improvements may be possible, particularly in cities where some companies are routinely busy more than 20 percent of the time. Before describing these models, it will be helpful to review some features of traditional dispatching procedures.

In most fire departments, "running cards" (sometimes called "alarm assignment cards") play a fundamental role in the initial dispatch and redeployment decisions. One such card (from Denver) is reproduced in Fig. 7. At the top, it lists the companies in order of their distance from the location (in this case, all alarm boxes in group 2-19). The companies on the first line constitute the full first-alarm assignment, those on the second line the second-alarm assignment, and so forth. A typical initial dispatch policy might be (in part) as follows:

Type of Alarm	Decision
Telephone report of a rubbish or automobile fire	Send the first engine on the card
Telephone report of a fire in a building	Send the engines and ladders on the first line of the card
Pulled street box alarm	Send the first two engines and first ladder on the card



2-19

ENGINES	TRUCKS	SQDS.	CHIEFS	BOX LOCATIONS DFD 5 1 66
1 4 5 6	1 4	2	2 5	
2 3 7 8	6		6	
12 13 21	11			
10 18 20				
CHANGE OF LOCATION				
21-4 12-2 13-1 17-6	10-4 11-1 17-R17		4-FAO 7-1	
18-4 20-1 23-20	15-1 14-15		4-10	
16-13 11-4 23-1 R23-20	23-R23			
ORDER OF RESPONSE				
2-3-8-7-10	6-10-11	2-8	4-6-3	

Fig. 7 — A running or alarm assignment card

This specification of a standard initial response for different kinds of alarms may vary in other ways also: The number of companies to respond initially may vary from location to location, with more companies specified for locations with known high hazards (lumberyards, hospitals, etc.). A less common practice is to vary the number with the hour of the day, the season of the year, the weather, or the past history of alarms at the location.

An implicit assumption in the use of running cards is that all the companies listed will be available for dispatch when the alarm is received. In the past, this was almost always true, but with recent increases in alarm rates it is becoming more and more common that one or more of the companies that are to be dispatched are unavailable. This is particularly true in cities where fire departments are responsible for emergency medical services. In some instances, the dispatcher will "replace" an unavailable company with another company on the next line of the running card; in others, he will not, and fewer companies will be sent to the incident. In some cities the dispatchers have some discretion in this matter. Sometimes additional information is used. For example, the dispatcher may be required to find a substitute for an unavailable company if there is an indication that the fire is serious (for example, when two or more telephone calls report the same fire).*

The practice of sending a reduced response when some of the companies on the first line of the running card are unavailable may be more widespread than previously suspected. Because there is a natural reluctance to acknowledge that less than the standard response might sometimes be dispatched, it may be necessary to observe dispatching operations or look at dispatching records to find out what the current dispatching procedures actually are. Our term for sending fewer than the standard number of companies when some of those on the card are unavailable is "de facto reduced response."

With this background on traditional dispatching procedures, we are now in a better position to describe some of the dispatching models that are available. These fall into two categories. The first consists of descriptive models that help in evaluating how well different dispatch policies perform. The second are models that attempt to prescribe what a good dispatching policy should be.

We discuss descriptive models first, beginning with one designed to predict the extent of de facto reduced response, and the consequent effect on travel times [17]. For alarms where substitutes are always found for unavailable companies, de facto reduced response does not occur. For alarms where unavailable companies are not replaced, the model estimates the fraction of those alarms that receive the standard response and the fraction that receive fewer. For example, consider the situation described in Table 1 of Chapter 2. An average of 9 of the 11 engines assigned to the region are available. If the standard response is two engines and unavailable engines are not replaced, the model estimates that 67 percent of the alarms would be sent two engines initially, and the remaining 33 percent would get fewer.*

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*Note that we are considering the question of replacing unavailable units only on the initial dispatch. We are not considering here methods by which reports from units that reach the scene can be used to adjust the initial response.

We have found that producing such a figure is useful in initiating an open discussion of de facto reduced response and its implications within the department. The number of alarms that do not get the standard response is often higher than might have been guessed, and the model reveals the difficulty of trying to reduce this number by adding new companies to the force. Continuing the example, if three more engines are assigned to the region (bringing the total to 14), 74 percent of the alarms in question would get the standard two-engine response†--not much of an increase over 67 percent.

By considering the proportion of the city's serious fires that are of each alarm type, these estimates of the extent of de facto reduced response can be used to compute an indicator of "response adequacy." That is, the proportion of serious fires that are dispatched at least two engines (or three or more engines) can be computed. And by considering the delay until the response is "filled out" and using the square-root law and the travel-time equation, one can compute the average time from the dispatch of the first company until the arrival of the last of the companies specified by the standard response.

The kind of analysis just described deals with alarms in an aggregate way and gives average values for performance measures. Using a computer simulation model, such as the Institute's Fire Operations Simulation Model [1,2], we can obtain more detailed results, such as the proportion of alarms with response times of less than 5 minutes and the number of responses and working hours of individual fire companies. A simulation model also allows us to evaluate a wider range of policies.

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*The chance that two are dispatched when the standard response is two and unavailable engines are not replaced is estimated by

$$\left(\begin{matrix} \text{Average} \\ \text{number} \\ \text{available} \end{matrix} \Bigg/ \begin{matrix} \text{number} \\ \text{assigned to} \\ \text{the region} \end{matrix} \right)^2 .$$

In the example, then, $(9/11)^2 = 9/11 \times 9/11 = 81/121 = .67$.

†$(12/14)^2 = .74$.

These benefits come at a price: The computer program is large and relatively expensive to run; an experienced programmer will be needed; and detailed data, including geographical representation of company and alarm locations, must be specified.*

The simulation model will predict response times and other performance measures for different policies. But it will not in itself suggest what policies to try. So we turn now to prescriptive models. Unfortunately, with the current state of knowledge concerning the relationship between the number of units dispatched to fires and the resulting fire losses, it is not possible to specify a "proper standard response" to street box alarms or to telephone reports that appear to be for structural fires or other types of alarms. For example, to determine eventual fire losses at fires that require two engines, we know of no systematic study of the difference between (1) dispatching two engines initially, and (2) dispatching one initially, with the other sent when the first reaches the scene.

A useful approach [29] bypasses this lack of knowledge with the following assumptions: (1) As each alarm is received, a reliable estimate can be made of the chance that it signals a serious fire and that this chance varies from alarm to alarm.† (2) The availability of nearby companies and the alarm rate in the near future are known. Thus, average response times to serious fires are minimized (with more weight on the first engine than on the second and more weight on the first ladder than on the second).

The analysis indicates that the chance that the alarm signals a serious fire is the most important factor to consider, and a good rule for ladders is of the form "if the chance that the alarm signals a serious fire is greater than a cutoff value, send two ladders; otherwise, send one." The department must specify the cutoff value. (The rule for engines is analogous.) Some features that distinguish this policy from traditional dispatching policies are:

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*For a more detailed discussion of when a simulation is appropriate, see Ref. 2.

†Reference 5 confirms that both assumptions are true in New York City.

1. This policy always replaces unavailable companies.
2. Because the chance that an alarm signals a serious fire changes with time of day at a given location, the standard response would also change with time of day.
3. The standard response for different types of alarms (where type is determined by what the dispatcher knows) depends on the chance, as predicted by analysis of the historical data, that each alarm signals a serious fire.

Reference 18 provides a useful introduction to this question of how many companies to dispatch. Comparisons of policies that replace unavailable units with policies that do not are given in Ref. 4. A detailed description of the method that will be used to determine the fire companies to be dispatched to alarms in New York City is planned for future publication. The results of using such a policy can be an appreciable increase in the fraction of serious fires that receive an "adequate" initial dispatch and consequent improvement in response times, without increasing the total number of responses to all incidents.

On the question of which companies to dispatch, surprising as it may seem, there are some circumstances in which a more distant company should be sent, leaving a closer company in its house. In particular, it may be better not to send the closest available company in an area of the city where (1) the alarm rate is expected to be high, (2) the incident in question is unlikely to be serious (for example, a telephone report of burning rubbish), (3) the more distant company is not much more distant, and (4) the closer company is more likely to be needed at another incident soon. Such a policy can result in both an improvement in response times to serious fires and more equal distribution of work among the companies. See Ref. 3 for details.

Chapter 7

STEPS IN DEPLOYMENT ANALYSIS

A project to analyze deployment problems may begin in either of two ways. In one, political or other developments outside the department may force consideration of a particular policy issue. For example, the boundaries of the department's jurisdiction may change, or its budget may be reduced, or an existing firehouse may become unsuitable for future occupancy, or a regional dispatching center may be constructed, or the workload of certain companies may increase rapidly.

In the second, the department's management may wish to explore the possibilities of improving operations using the techniques described in this report, even though there is no pressing need to do so. Such an analysis should begin with an exploration of the possible policy issues that might be addressed and the likely costs and benefits of pursuing each one of them. A planner having some technical skills and familiarity with the department's management operations and data-processing capabilities should be assigned to this exploratory review. He should be given at least a month to read carefully the relevant references in this report and to make further inquiries by telephone calls or, preferably, site visits to departments that have already used the methods we have described.

In some cases it will not be possible to know whether a deployment problem exists until preliminary data collection and analysis have begun. The Parametric Allocation Model (described in Chapter 4) was specifically designed to help a department determine whether its current allocations of fire companies to regions of the city are satisfactory or not. It can be used with very little data and a few days' or weeks' work. If the results reveal that no changes in station locations are needed, the project can be terminated, or attention can be given to other policy issues such as dispatching practices.

Once the issue(s) to be addressed have been identified, the next step is to select the *methods* to be used. Although this report gives general guidance, planners should conduct a careful *search* of the available options. This will involve reading the appropriate references already given in this report and also reviewing related summary documents [8,30]. Site visits to other departments that have previously installed one of the models should be conducted at this time if not included in the exploratory review. These visits are valuable to obtain frank opinions and useful advice. Selecting the most appropriate existing computer program for a particular application, or deciding to develop one's own programs, is an important choice that should not be treated casually.

Next, the department will have to determine whether its own personnel are capable of conducting the study or whether outside assistance is required. Fully documented simple models such as the Parametric Allocation Model and the Firehouse Site Evaluation Model can be used without special programming or statistical skills; the department needs merely to have access to a portable computer terminal. The Fire Station Location Package is also fully documented and has been used without outside assistance in many communities. Other models, such as simulation models, may be too complex to operate properly without outside assistance, or they may be available only as part of a "package deal" that includes consulting services. If the department requires outside assistance, local consulting firms or university professors and students are possible sources within the community.

A project team should be assembled, consisting of the department's planners, outside analysts, administrators who will be called on to make the final policy decisions, the chief who will have to implement them, and possibly representatives of labor unions if negotiable issues are under study. No policy change, however logically related to performance measures, can succeed if it is infeasible for reasons that were not taken into account. Assembling an appropriate project team will prevent producing the "perfect" deployment plan that is never implemented. The Denver case study [14] contains a complete description of the organization of the project team and policy review committee in that city, and it can serve as a useful guide to others.

To familiarize all the members of the project team with the steps to be followed in the analysis, data requirements, and capabilities of the computer models, some type of training should be conducted. A formal training course, perhaps using guest lecturers, is a possible approach. Lecture notes, visual aids, and examples of demonstrations of computer programs are available for this purpose, as noted in the Preface.

Soon after the project is organized and the team members are trained, attention should focus on arranging for the availability of appropriate data when they will be needed. Almost all fire deployment studies will require summary statistics concerning alarm rates broken down by type, time of day, and geography. A department should develop the capability to obtain data that can be processed by computer, showing the time of arrival of each alarm, the type of the alarm, and its location. This information is needed for at least a one-year period and may be collected either by installing a new data system and waiting a year before beginning analysis or by coding data from past records. The Uniform Fire Incident Reporting System [31] is compatible with most deployment analyses.

The number of companies working, the times at which each arrived at the incident, and the amount of time each worked will be useful, but it may be difficult to record this information for every alarm. Instead, it can be collected for a suitable sample of alarms, say, all alarms over a two-month period or over selected hours in several months.

The location of the alarm must be specified to a level of detail appropriate to the studies that are being considered. Many departments reference every alarm to the closest alarm box or street intersection. This level of specification is ideal and should be entered onto the computer-readable record for every alarm (not only for box alarms). Other departments record the address of each incident. In this case, a computerized or manual address-matching process will have to be used to determine the appropriate "subarea" for each address.

It is important not to consider the collection of data as an end in itself. There is a tendency for department planners, once they have obtained appropriate summary statistics, to send them immediately to the chief. The planners want to prove that they have accomplished a major task. But performance statistics alone, without an indication of their implications for policy, are practically useless and may lead the chief to doubt the abilities of the planners. Therefore, it is important to *do something* with the data. Through analysis, the policy implications of the data can be determined. In fact, it may happen that the data reveal an unexpected deployment problem, leading to a change in the objectives of the project team.

Next comes the step of generating alternative deployment strategies and estimating their impacts by using the computer programs. Although in most instances complete user's manuals are available to instruct the project team in this process, experienced planners know that unanticipated problems may arise before the program operates properly with the department's data base. It is important to try out the *base case* (namely, the department's current operations) and to compare the estimates provided by the model with actual data to the greatest extent possible. This may reveal errors in data collection, especially if some of the data were "guessed." For example, a department may have trouble believing that the cruising speed of its units is 36 miles per hour (as implied by the travel-time curve in Fig. 2). But if this speed, when entered as data in a model, gives estimates of travel times that conform to reality, it should be used.

The final step, developing policy recommendations and new deployment strategies, may be the most difficult. The models do not make decisions. Rather, they provide quantitative information to aid local decisionmakers in objectively assessing the impact of deployment options. Local administrators must then determine what appears "best" in light of local needs and budgetary, political, and other constraints.

Appendix

ADDRESSES FOR FURTHER INFORMATION

For copies of publications and computer programs developed by The New York City-Rand Institute, inquiries regarding training materials, and questions about this report, contact

Jan M. Chaiken
The Rand Corporation
1700 Main Street
Santa Monica, California 90406
(203) 393-0411

The research sponsor of this project is:

U.S. Department of Housing and Urban Development

Alan Siegel, Director
Hartley Campbell Fitts, Chief

Community Management and Productivity Improvement Research Staff
Office of Policy Development and Research
451 Seventh Street, S.W.
Washington, D.C. 20410
(202) 755-6970

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